Water harvesting in Mediterranean zones:
an impact assessment and economic evaluation

Proceedings from EU Wahia project final seminar in Lanzarote

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FOREWORD

This book constitutes the proceedings of the final seminar of the European Union-funded research project 'WAHIA' (Water Harvesting Impact Assessment) held in March 2002 on Lanzarote (Canary Islands). It covers the research results of this project, which was executed in southern Tunisia and southern Morocco by a consortium of Wageningen University (The Netherlands), 'Institut des Régions Arides' (Tunisia), University Ibnou Zohr (Morocco) and University of Gent (Belgium). And it also presents similar research undertaken by the University of La Laguna (Canary Islands).

In 1997 a meeting was held in Wageningen, The Netherlands, between representatives of the Tunisian Institute of Arid Regions (IRA) and the Universities of Gent and Wageningen, which resulted in a draft research proposal on 'Impact assessment and economic evaluation of water harvesting systems in dry mediterranean zones'. The University Ibnou Zohr was interested to join this project, and the final proposal was submitted to and later honoured by the European Commision's Directorate General of Science, Research and Development (DG XII) for financing under its INCO DC (Cooperation with Third Countries and International Organisations) programme.

The main objective of the WAHIA project was to develop a methodology for impact assessment and economic evaluation of water harvesting techniques in dry Mediterranean areas. These techniques contribute to the conservation of land and water resources and help increasing or at least maintaining agricultural production in these areas.

In order to reach this objective, the project first made an inventory of water harvesting techniques in two selected zones (sub-catchments), namely the Oued Oum Zessar watershed near Médenine in southern Tunisia and the Talkjounte watershed near Taroudant in southern Morocco. In each of these research areas, three water harvesting techniques were selected and their physical effects identified and quantified within their micro-catchments. This was done for jessour, tabias and groundwater recharge structures in Tunisia and for seguias, wells and a dam with hill-side lake in Morocco. Extensive monitoring of meteorological, hydrological, hydro-geological and erosion and sedimentation parameters was undertaken to this aim. Additionally, models and modules were developed that could simulate these physical effects and which could subsequently be used to extrapolate measured values in space and time. Both measured data and simulated data were used as input for the impact assessment, whereby the various physical effects were translated in productivity and other economic parameters, making it possible to undertake an economic evaluation of these selected water harvesting techniques. Interviews were conducted among beneficiaries of water harvesting techniques and other relevant actor groups in order to collect socio-economic data necessary for the economic evaluation. Different economic evaluation methods (conventional and extended cost-benefit analysis and multi-criteria analysis) were chosen depending on available data. An economic evaluation was also made at the catchment-scale for the Tunisian watershed, and more in particular of the activities implemented under the national strategy for soil and water conservation in this area. Finally, the project developed a tool for decision-makers which serves to make an assessment of the potential role of water harvesting techniques with regard to the mobilisation and management of water resources in other dry Mediterranean zones.

Through this detailed impact assessment and economic evaluation this research unravelled why certain traditional water harvesting techniques have been successful in the past, and how effective and efficient new ones may be. The importance of considering off-site effects was clearly demonstrated and this was identified as an important issue for decision-makers, as they will need to analyse how best use is made of scarce water resources and what conditions (transfer payments, incentives) might be necessary to achieve this optimal situation. With the aid of the decision-making tool, planners, development agencies and others can make an analysis of which type of water harvesting techniques may be used where and under which conditions and what effects can be expected on local and downstream physical and socio-economic parameters.

Although the project has reached its main aims, it has suffered from a few set-backs. It was confronted with two very dry years with only few rainfall events contributing to runoff. This has hampered physical data collection, and made it difficult for the economists to use these data for assessing the economic impacts.

During the course of the project several meetings and seminars and on-the-job training courses were held on erosion research, modelling, impact assessment and economic evaluation. The final project results were presented at the last project seminar held at Lanzarote, Canary Islands, and hosted by the University of La Laguna. As mentioned above this book constitutes the proceedings of this seminar.

Acknowledgements

The WAHIA project staff thanks local field staff from institutes in Tunisia and Morocco and farmers in the two watershed areas for the pleasant collaboration on the project. We also thank the students from the four institutes for their enthusiastic participation in the project: N. Ayadi, R. Barneveld, M. Fetoui, S. Heirman, M. Issaoui, M. Jebadi, R.A. Lelivelt, M. Maati, A. Nazih, A.M. Sow, Salles, S. Tanghe and D. van de Voort.

The final project seminar was smoothly organised by Professor M. Tejedor and Mrs. C.C. Jiménez of the Universidad de la Laguna on Canary Islands, for which we thank them very much. We also express our high appreciation to Mr. Reyes Rodríguez, the major of Yaiza on Lanzarote, for facilitating the organisation of this seminar, and to the municipalities on Lanzarote and Fuerteventura that organised the very interesting excursions to water harvesting sites on the two islands. At this seminar the final results obtained in Tunisia and Morocco could be confronted with traditional water harvesting and cropping systems in the Canary Islands.

The WAHIA project has been made possible through a research grant (IC18 CT980269) of the European Commission. We would like to thank the European tax payer for the trust that was given to the four partners. We thank the Project officer Mr. F. Kaser and the Financial officer Mr. P. Tzimas for all the work they undertook for the project on behalf of the European Union. And we thank Mr. R. Alink and Mr. E. Ploegmakers, financial officers of the Department of Environmental Sciences of Wageningen University for all the project administration. Luuk Fleskens and Christian Siderius provided editorial assistance.

INTRODUCTION

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The most dominant feature of the Mediterranean eco-system is its rainfall. Scarce rainfall occurs in winter, the non-growing season, and large inter-annual variations are the rule rather than the exception. Since ancient time, conservation and cropping systems have developed that are well adapted to the peculiarities of this rainfall. In the past high investments have been made in techniques for the harvesting and storing of water. Man and animals have often survived bad rainfall years on water stored in cisterns.

There exist many different ways to harvest and store water. Conservation of water in the topsoil during wintertime for subsequent use by spring wheat is one example. A whole year's fallow, to conserve water for the next year, is another example. Storing water in deeper layers, below the sphere of influence of annual crops, is another common practice. Wells, fed with groundwater are at the base of many indigenous irrigation systems in the Mediterranean like the seguia system in Morocco and the oasis systems in Tunisia. Besides traditional systems, also new systems have been developed, like the many new structures used for the recharge of groundwater.

The many different opportunities to harvest and store water and the high variation in other natural resources have created a multitude of complex conservation based cropping systems. Most systems rely on a mixture of annual and perennial crops complemented with animal husbandry. Olives, the oldest fruit tree in the world, survive the large inter-annual variation thanks to water stored in deeper layers. In many cases water harvesting and nutrient management go hand in hand. For instance, the Jessour system in Tunisia is based on the intricate management of an impluvium that serves both water and nutrients for small areas behind dams.

The history and functioning of these indigenous systems give rise, nowadays, to two interesting questions. The first is whether the systems are still viable under present-day economic and social conditions. And the second, related, question is whether expansion of these systems is still possible given the high investments costs. The viability of agricultural production systems or, to use a modern buzz word, their economic sustainability depends on the relative pricing of the many inputs and outputs that play a role in farming. Straightforward examples of I/O's are the market prices for fertilizer, machinery, hired labor and produces like wheat and olives.

A three-years (1999-2001) research, funded by the European Commission under the International Cooperation program, addressed these questions. The project 'Water harvesting techniques in dry Mediterranean zones: impact assessment and economic evaluation' is better known under its acronym, WAHIA. The impact study included the bio-physical and the present-day socio-economic functioning of these systems. In the first part traditional water harvesting and production systems were identified in Tunisia and Morocco. The indigenous 'jessour' terraces, groundwater recharge and the 'seguia' irrigation ditches were chosen for detailed study. It took a large effort to quantify, through measurements, the various functions.

In other to evaluate these systems, a format for the economic assessment has been developed. The data from the detailed studies have been used for this. It may well be, like in many parts of the world, that due to fast general economic development traditional systems are no longer considered sustainable, at least under classical capitalist free market principles. Examples of consequences of general economic development that hurt the more traditional production systems are: (1) the unfavorable reward for labor between the on-farm and off-farm employment, especially in areas with tourism development, (2) the world trend of over-production and subsequent low prices for most commodities. However, land use nowadays is no longer determined by classical economic principles only. New economic paradigms pop-up, often under popular pressure, that favor local social values or the environment. The free-market principle does not always hold with respect to land use, at least not fully. Land and landscapes are becoming more multi-functional.

Finally, on the basis of our work, some policy implications could be formulated. It can well be that a traditional production system with inherent water conservation is no longer viable under present-day classical economic variables used for agricultural in- and outputs. The same system can, however, be viable if social, environmental values are taken into account. Or, if other sectors of the economy give a price to the traditional production system. Many examples of this can for instance be found in tourist areas. Oasis systems are typical examples. Although one can imagine that this new insight prolongs the life of existing systems it still remains to be seen whether investments will be done in the expansion into new systems. If traditional systems seem no longer economic viable, they can only be maintained and new systems installed by public intervention. That is by appropriate incentives for the farmers.

WAHIA has contributed to the understanding of traditional water harvesting production systems and has developed a methodology that can be used to value such systems in multi-functional landscapes and to determine whether new investments should be made. WAHIA has presented and discussed its results during a conference held in Lanzarote in March 2002. Results obtained in Tunisia and Morocco were confronted with long-time practices and experiences in the Canary Islands. Results of this conference are published in this book.

The book is divided in three parts, in line with the project's work packages and also in accordance with the planning of the last project seminar. In the first part the results of the inventory studies on water harvesting techniques (WHT) are presented, for the two project areas and for the Canary Islands. A series of photos is thereafter presented, to give the reader an idea about the respective WHTs. The second part deals with the results of the hydrological and erosion studies, which provided insight into the physical effects of the WHTs. And the third part discusses the results of the economic impact assessment and evaluation of the WHTs, whereby the physical effects are translated in productivity and other economic parameters.

Part I :

Inventory of water harvesting techniques

1 TRADITIONAL AGRICULTURAL PRACTICES IN THE CANARIES AS SOIL AND WATER CONSERVATION TECHNIQUES

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Abstract
The islands of Lanzarote and Fuerteventura in the Canary islands (Spain) are among the most arid regions of the European Union, bordering on desert conditions. The unfavourable conditions –climate, soil, sparse vegetation and lack of water- are conducive to degradation processes leading to desertification. Dryland farming is ruled out because of these environmental conditions. Down the years local farmers have developed agricultural techniques to conserve soil and water and allow a small amount of cultivation without irrigation. These systems involve either the covering of soils with volcanic materials, which act as a mulch, or the harnessing of what little run-off water exists. The present work describes the main systems, focusing mainly on the first type just described. The properties of the mulched and unmulched soils are compared: moisture content at different depths, evolution over time, temperature, effects on salinity-sodicity, etc. All the results obtained point to the technical effectiveness. These systems are in decline today not so much for reasons of effectiveness but due to socio-economic factors.

Keywords: Soil and water conservation structures, volcanic mulch, traditional farming systems, conservation agriculture

1.1 Introduction

Arid and semi-arid zones account for approximately one third of the earth's surface and affect some 16% of the population (UNESCO, 1995). The climates and soils of these zones are an impediment to agricultural production, whilst at the same time leading themselves to desertification processes. Down the years soil and water conservation techniques for farming have been developed in such parts, many of them being valid models of sustainability (Gale *et al.*, 1993; Chesworth *et al.*, 1994; Kamar, 1994; Doolittle, 1998; Nachtergaele *et al.*, 1998). Examples of these agricultural systems can be found in the arid parts of the Canary Islands (Fernández Caldas and Tejedor, 1987; Jiménez *et al.*, 2002).

The Canaries are an archipelago in Spain and comprise seven islands, with a combined area of 7,541 km^2 and maximum height of 3,718 m.a.s.l. The islands' climate is extremely varied due to a number of factors, notably the trade winds, relief, orientation of the mountain ranges and altitude. In the more mountainous islands, the northern side is humid and cool, due to the influence of the trade winds, whereas the southern side is arid and warmer, as are the flat islands (Fuerteventura and Lanzarote).

Lanzarote, which is 846 km^2 in size, is the eastern-most island in the archipelago, lying a mere 125 km off the western coast of Africa. It is also the least mountainous of the islands, reaching a maximum height of 670 m.a.s.l. Its official population, in 1995, was 76,413 inhabitants although the real figure is 113,360 due to tourism, making for a population density of approximately 134 inhabitants per km^2 (Hernández, 1999). The island receives one and a half million visitors every year and tourism has fast become the mainstay of the local economy, to the detriment of other sectors such as agriculture.

The island has suffered major volcanic eruptions that have resulted in emissions of abundant pyroclastic materials, a circumstance that has propitiated the development of farming techniques based on the use of these materials as mulch. The present work examines these practices mainly in the island of Lanzarote. First, the characteristics of the environment in which these agrosystems are used will be described. Then, a discussion will follow on their design features and show how they enhance some of the properties of the soils.

1.2 Environment

1.2.1 Climate

The climate parameters are typical of a very arid climate. Annual rainfall tends to be less than 150 mm with considerable variations from year to year. Rain falls during the winter months and the greatest amounts of water come from torrential south-easterly and south-westerly storms. Average annual temperature is around 20°C-21°C with notable differences during the course of the day (sharp falls in temperature at night). Winds are strong and constant year-round, with an average speed of 20 km h^{-1}. Sunshine is plentiful, with an annual average of 7.8 hours per day. The evaporation rate is high, at approximately 2000 mm in evapometric tank. Relative air humidity is also high with a daily average in excess of 70%, an important circumstance given the possibility of condensation water uptake and its role in the operation of the agrosystems described here.

On the basis of the different climate indices, the climate of the study zone is classified as Desert (Lang index), Hyperarid (De Martonne) (Porta, 1994), and semi-arid tropical Mediterranean (Papadakis, 1960). The years during which the soils in the agrosystems were monitored (March 1998-April 2001) were particularly dry. In a representative weather station the annual rainfall collected was 72.6 mm in 1998, 98.0 mm in 1999 and 47.1 mm in 2000.

1.2.2 Geology

Like the other Canary Islands, Lanzarote is of volcanic origin and has suffered the most prolonged recent eruptions (1730-36) during which the greatest amount of materials in the archipelago's recent volcanic history were given off (Carracedo *et al.*, 1998). The pyroclasts and outcrops emitted covered a substantial part of the island's soils and led to the birth of these striking systems, *arenados*, thanks to which dryland farming is possible here. Predominant are basaltic materials dating back to between 1824 (last eruption) and the later Miocene.

Aeolic formations are also abundant in Lanzarote. These are organogenic calcareous sands, which were blown inland from coastal areas and, during the Quaternary period, covered the soils of the central part of the island (Fuster *et al.*, 1968). These sands, known locally as *jables*, a term derived from the French word *sable*, have also given rise to another agrosystem, described here also and called *jable* as well.

1.2.3 Soils

The chief factors responsible for the origins and dynamic of Lanzarote's soils are aridic moisture regime, scarcity of vegetation and the age of the geological materials. Other contributing factors are, in the majority of cases, contamination by aeolian dust from the Sahara Desert, degradation processes, human actions and human pressure on the territory. As a result of all these factors, the soils present very specific characteristics, such as low organic matter content and low biological activity, alkaline reaction, horizons with accumulations of carbonates, soluble salts, sandy-loamy surface texture, modified soil surfaces: desert pavement, sealing crusts, etc. However, considerable variations in the texture of the deep horizons, structure, depth of profile, types and amounts of the saline accumulations etc, are found from one soil to another, especially with regard to the age of the materials, topography and erosion (Fernández Caldas *et al.*, 1987). The soils found on the island are, according to the Soil Taxonomy 1999 (Soil Survey Staff, 1999), and the nearest equivalent in other classification system (FAO, 1998), as follows:

Table 1.1. *Soils*

SOIL TAXONOMY, 1999	*WRB (FAO, 1998)*
Vitritorrands	Vitric Andisols
Calcitorrerts	Calcic Vertisols
Argids, Calcids, Cambids	Luvisol, Calcisols, Cambisols
Psamments, Fluvents, Orthents	Arenosols, Fluvisols, Leptosols/Regosols

These soils were clearly formed in different climatic conditions. The origins of the fersiallitic soils with deep clayey alterations and the Vertisols, which are normally underground, appear to be associated with a warm climate with clearly distinct wet and dry seasons. The distribution of carbonates in the soil and the erosion and colluviation processes are associated with subtropical semiarid climatic conditions, while the current, more arid climate triggers deeper carbonisation in existing soils and contributes to processes of degradation rather than formation. Tephra mulch brings about a change in the soil moisture regime, which switches from aridic to udic in some cases (Tejedor *et al.*, 2002a).

1.2.4 Water

Due to the arid climate and other factors, water is in very short supply in Lanzarote. Indeed 90% of the water consumed is derived from desalinated sea water. Of the little rain that does fall in the Lanzarote Island, 96% is lost through evapotranspiration, 1% through runoff and some 3% infiltrates. Surface water is collected in reservoirs and by runoff harvesting, while groundwater is extracted from wells, although in this latter case output is low with poor water quality. In the above-described environmental conditions different types of dry farming have evolved.

1.3 Water Harvesting Systems

1.3.1 Systems based on runoff harvesting

The following two systems can be identified:

a) *Gavias*: Systems designed to harvest runoff water. Located in flat or barely sloped parts, usually foothills, and built perpendicular to the highest slope generating the runoff (Jiménez *et al.*, 2002). The system is shown on photo 1 (see photo-page after chapter 3).
b) *Nateros*: Operates on a similar basis as the gavias. Built on the beds of small ravines, they involve the erection of a wall, usually made with earth, perpendicular to the runoff. The wall retains not just the water but also the fine elements carried along with it.

1.3.2 Systems based on surface mulching

Four different systems based on surface muching can be found.

a) *Natural arenados* are used in areas that have natural presence of tephra and are located near volcanic cones. They are shown on photo 2. The layer of the covering can be quite thick but is most frequently around three metres. For each plant a hole of around 3 metres wide in diameter is dug (to a depth which depends on the thickness of the ash covering) to reach the soil level, where the planting takes place and a layer of manure added on top. The plant is thus in contact with the soil below and is protected from the wind by the hole. Furthermore stonewalls are often erected around the hole. These are semicircular and face perpendicular to the direction of the prevailing wind. Fragments of the basaltic outcrops are used in the walls. This dry farming technique is very common, although it tends to be used only for vines or figs. The most characteristic natural arenado zone, which is used for wine growing, is known as The Geria and covers approximately 2,400 hectares. Some 2 million litres of internationally renowned wine is produced every year here.
b) *Artificial arenados* are made by the farmers in the same way as their natural counterparts in areas not covered by the volcanic materials. Volcanic tephra is placed over the soil, which may be either natural to the area or brought in from other parts, as is the case when the natural soils are too poor for agricultural purposes or are not readily available. The basaltic ash layer varies in thickness between 5-20 cm, with 10-12 cm the most common. Before the soil is covered with the tephra, organic material (usually manure) is added mechanically at a depth of around 10 cm. The average life of the system is approximately 20 years, by which time its effectiveness has diminished due to the tephra mixing with the soil. When this happens, the tephra surface covering is replaced by one that has not been contaminated by the soil. A layer of manure is placed on the ground before the new tephra is laid.
c) Crops grown in *cracks in the lava.* This occurs in parts where the soil was covered by lava outcrops. The farmers use the cracks in the lava to access the soil underneath for growing deep-rooted plants (vines and figs). The soil underneath tends to be superficially contaminated by the tephra, which acts as mulch just as in systems a) and b). Here too, protection against the strong winds exists.
d) Crops grown under *jable*. This form of cultivation takes place in central parts of Lanzarote covered by varying thickness of natural layers of aeolic sands from the sea. Crops tend to be grown in the areas where the sand layer is less than one metre. The procedure for growing the crops is similar to that described above for the artificial arenados: a hole is dug to soil depth, manure is inserted, and planting is done directly in the soil if the sand covering is thin. Where the sand thickness is greater, once the manure is laid the hole is

filled in with sand and the planting is done in the sand, near the surface. Protection against the wind is vital for these sand-grown crops. If no barrier is included, the plant risks ending up buried entirely in the sand. Like the tephras, the surface sand acts as mulch, reducing soil moisture loss. Although the system is less effective, it does nonetheless permit dryland farming of certain crops, such as sweet potato, melon, watermelon and pumpkin.

1.4 Influence of the tephra mulch on soil properties

Having described the main dry farming systems, we will now turn to the influence they have on soil water conservation, salinity-sodicity reduction, soil temperature and erosion control. We will focus on the case of the artificial arenados.

1.4.1 Soil water conservation

We monitored over three 3 years the moisture in the soils covered by tephra and in the adjacent uncovered soils. Sampling was done monthly, every 10 cm to a depth of 1 metre. Figure 1.1 gives the results obtained in one of the systems, which had a 12 cm layer of tephra. The percentage is given for the moisture content over the three years, expressed as a volume, for each of the depths, together with moisture content at 1500 kPa (wilting point). The chart on the left corresponds to the covered soil and the one on the right to the uncovered soil.

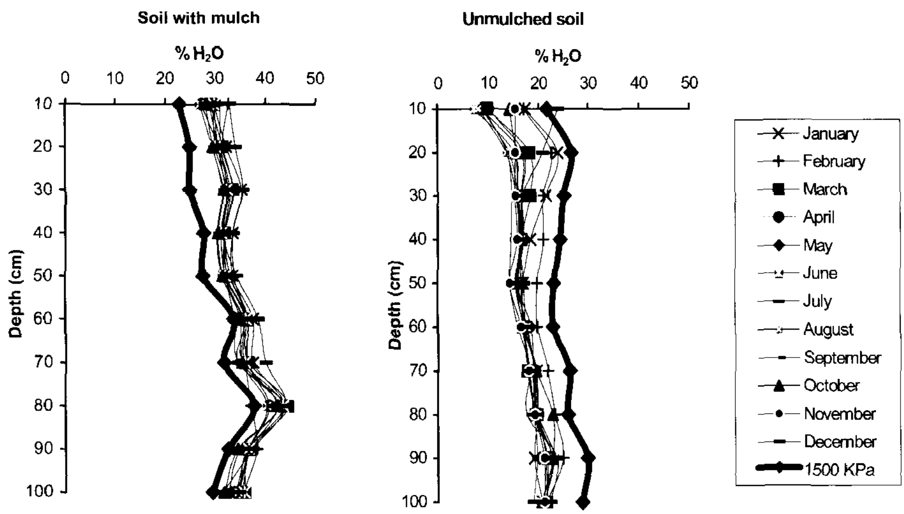

Figure 1.1. *Total gravimetric field and 1500 kPa water content in soil with mulch and unmulched soil*

Moisture in the covered soil remained above the content corresponding to 1500 kPa throughout the year, but below this figure in the uncovered soil (Tejedor *et al.*, 2002b). This circumstance enabled dry farming to be carried out in the former but not the latter.

Tephra grain size and the thickness of the covering proved to be extremely important parameters in terms of the results. Experiments with thickness of 5, 10 and 15 cm and three grain sizes (fine, medium and coarse) showed that the finest grains were more effective than the medium ones, and considerably more so than the coarse grain size. Regarding the thickness of the tephra covering, a vast difference was seen between the soils covered with 5 cm and those with 10-15 cm layers, in which behaviour was quite similar. In the latter case medium grain was used. The experiments are near completion and the results will be published at a later date.

The important influence exerted by the tephra covering on soil water conservation is, we believe, due to its physical properties, particularly its porosity, which favours infiltration of the island's scarce rainfall and also helps reduce water loss through evaporation. High environmental humidity and the considerable drop in temperature at night, added to adequate wind speed and the surface size of the tephra, combine to form ideal conditions for condensation, which is in fact seen early in the morning in the form of colour changes in the tephra. The tephra acquires a shiny black colour, which disappears gradually as it dries out during the day. One of the aspects we are working on at present is to estimate the amount of water produced by condensation, as well as the extent of uptake by the soil and the possible insulation effect.

1.4.2 Reducing salinity-sodicity

The tephra mulch exerts a major influence in reducing salinity and sodicity of the soils used for dry farming. Figures 1.2 and 1.3 give the electrical conductivity in the saturated paste (ECs) and exchange sodium percentage (ESP) values in the tephra covered soils and the adjacent uncovered soils. The first 30 cm of soil were used in each case and the soils were those in Fuerteventura where salinisation and sodification process are more pronounced. Each value shown represents the average for the 8 subsamples taken at random in the studied plots.

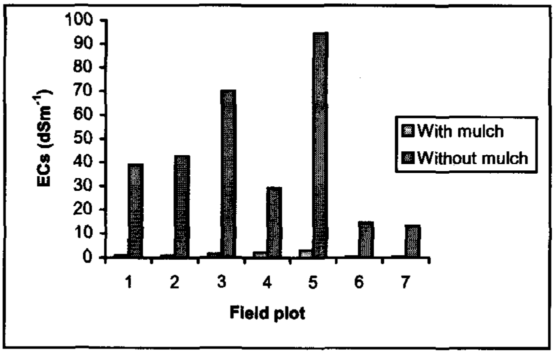

Figure 1.2. *Comparison of salinity in soil with mulch and unmulched soil*

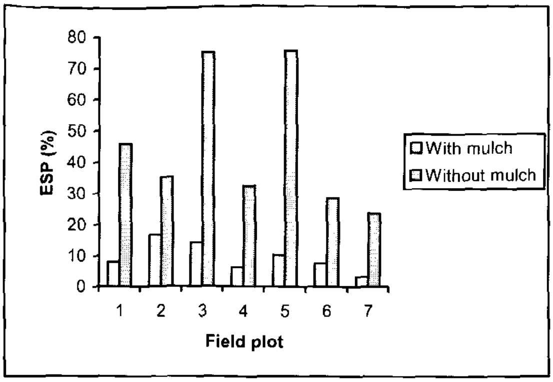

Figure 1.3. *Comparison of sodicity in soil with mulch and unmulched soil*

The non-covered soils are markedly saline-sodic, they present high electrical conductivity values and high percentages of exchangeable sodium. Conversely, when covered with a layer of tephra the same soils have very low ECs and do not reach 15% of ESP. Hence they are neither saline nor sodic (Tejedor *et al.*, 2002c).

The ease with which infiltration occurs and the mulching effect of the tephra layer, as was mentioned, have resulted in soluble salts lixiviation in what was originally a saline-sodic soil losing its salts when covered and the accumulation of the salts is avoided in the root zones. Increased dilution in soils under tephra, ease of Na ion washing and the possible dissolution of calcic salts as gypsum contribute to displacement of exchangeable Na in favour of Ca and hence the ESP values are reduced to limits that can be tolerated by the plants. This accounts for the reduced salinity and sodicity in the covered soils.

1.4.3 Soil temperature

The tephra mulch influences both daily and seasonal soil temperatures. Figure 1.4 gives the result of measurements taken on 6 August 1998, the month with the highest temperature in the year. Measurements were taken in the air, at 5 and 10 cm in the tephra and, in both the covered and uncovered soils, every 10 cm to 50 cm. Measurements were taken at 07:00, 10:00, 13:00, 16:00 and 19:00 h.

Temperature variations during the day in the uncovered soil are considerable up to 20 cm, the temperature reaching 46 °C at 16:00 h. In the covered soils, the temperature remains very even throughout the day and at all depths. The tephra layer exerts, therefore, a major buffering effect. The tephra layer also reduces seasonal temperature differences. Whereas the covered soils show differences between summer and winter of below 6 °C at 50 cm, the difference in the uncovered soils is higher.

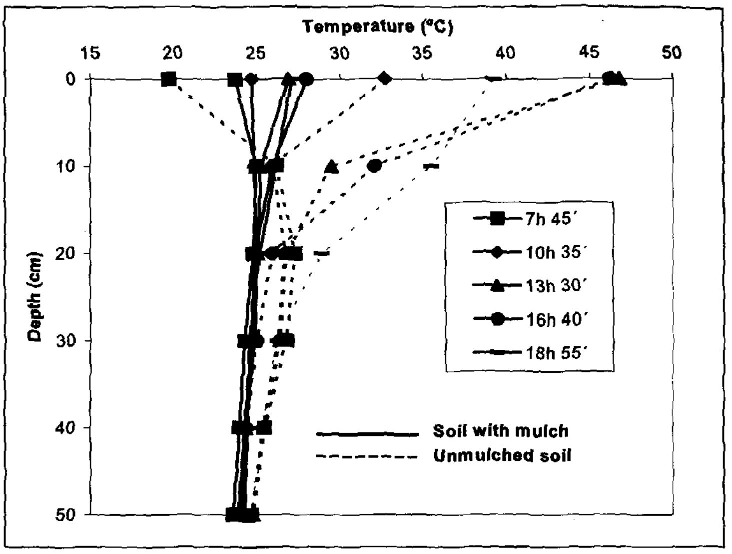

Figure 1.4. *Influence of tephra mulch on soil temperature*

1.4.4 Erosion control

Figure 1.5 compares the infiltration rate curves over time in a soil covered with tephra and in the same soil, uncovered. The study was conducted in a laboratory with a rain simulator, as follows: area 600 cm^2, soil height 15 cm, mulch height 5 cm, slope 6 %, average rain intensity 75 mm h^{-1}. The texture of the soil used was clayey; tephra grain size distribution was: 26.3% < 2 mm, 59.1% 2-6.3 mm, 14.6% >6.3 mm.

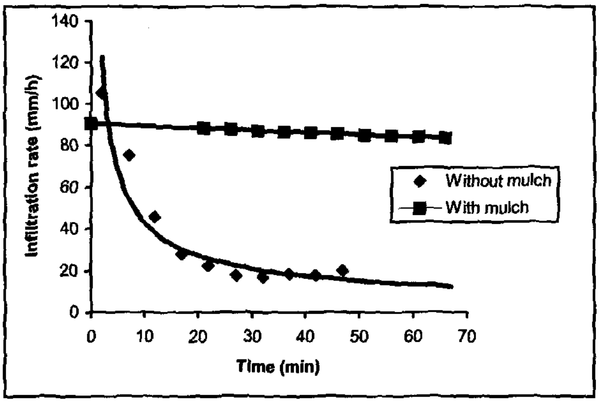

Figure 1.5. *Comparison of the infiltration rate curves in soil with mulch and unmulched soil*

In the uncovered soil the initial infiltration rate is seen to be high but it falls quickly and stabilises at a low value. In the soil under tephra the rate remains high at all times, and runoff is reduced. The system therefore aids soil conservation.

1.5 Production with WHT

The positive effect of the surface layer of tephra in soil and soil water conservation, among other things, is seen clearly in the fact that dry farming is rendered possible, when it would be completely ruled out were it not for the use of the technique. Average production between 1997-2000 for the three main crops was 8,043 kg ha^{-1} for onions, 6,030 kg ha^{-1} for potatoes and 907 kg ha^{-1} for grapes. It is worth noting that the production obtained with this system, using no irrigation, in extremely dry years such as 2000 (47 mm rainfall in the year) was 2,361 kg ha^{-1} for onions, 6,063 kg ha^{-1} for potatoes and 1,775 kg ha^{-1} for grapes. It is striking that under these very dry conditions potato production remained the same and grape production was even higher. The wine produced from the grapes -over 2 million litres per year- is of top quality.

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2 WATER HARVESTING IN SOUTHEASTERN TUNISIA: STATE OF KNOWLEDGE AND CHALLENGES

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Abstract

The south-eastern part of Tunisia has an arid Mediterranean climate where the mean annual rainfall does not exceed 200 mm. Rainfed farming, which represents an important component of the agricultural production system, is supported mainly by the water harvesting techniques.

For centuries, numerous techniques have been developed to make the land productive despite the harsh environment. The *jessours* are used to bank the runoff from the Matmata mountain chain. Cisterns, called *fesquia* and *majel,* are also contributing to the storage and exploitation of rainfall waters. Recently, other newly introduced techniques have been also adopted. The *tabias* are now widely used in the piedmont areas where the fruit trees (mainly olive and almond) groves are gaining large areas at the expense of grazing lands. The gabioning technique has been very attractive and hundreds of units are installed on the main wadi courses as small check dams or spreading structures for diverting runoff waters. In some cases, recharge wells are used also in combination with gabion units for aquifer recharge.

The water harvesting techniques are well adapted to their physical and social environment. They are playing various agro-ecological roles such as, water supplementation, flood prevention, water table recharge, and water and wind erosion control.

With the implementation of the national strategies for soil and water conservation and water resources development, most of agricultural lands would be under conservative measures and accessible water would be mobilised. More attention is therefore needed to assess the various impacts of combining old and newly introduced water-harvesting techniques. On the basis of local know-how, management methods in the future must fit better the current socio-economic context, in order to ensure a sustainable agricultural development of the dry regions.

Keywords: water harvesting, arid, rainfed, Tunisia

2.1 Introduction

Localised in North Africa, the climate of Tunisia is influenced both by the variability of the Mediterranean and the caprices of the Sahara. The arid, semi-arid and desert bioclimates cover more than two-third of its area (Floret and Pontanier, 1982). The rainfall regime is known by its scarcity, unpredictability and torrential character and the water balance is almost negative around the year (Hénia, 1993). Numerous civilisations and populations who lived in this country succeeded to build flourishing civilisations. Archaeological evidences and various old structures still in function are good indicators of people's perfect adaptation to natural environment (El Amami, 1984). Rainfed farming in Tunisia represents an important component of the agricultural production system. And, as in many countries in the world with similar environmental conditions, it has been supported mainly by the various water harvesting techniques (WHT), developed since the antiquity (Mainguet, 1991; Boers and Ben-Asher, 1982). A wide variety of small to medium sized hydraulic techniques have been introduced during many centuries to make the land productive irrespective of its geographical location. In fact, by crossing the country from north to south one can notice easily that each agro-ecological zone is characterised by its specific water and soil management structures (El Amami, 1982, 1984). Hence, the *meskat* has been behind the installation of important olive tree orchards in the Sahel region. In central Tunisia, floodwaters have been used to irrigate naturally the bordering areas of big wadis by means of *mgoud* technique. The Matmata mountainous chain in the south-eastern region has been terraced by jessour. Cisterns (*majel and fesquia*) and different conveying water structures (*khriga*) have been also contributing to the storage and exploitation of rainfall and ground water.

By the orientation of the Government to the installation of large hydraulic infrastructure (e.g. dams) dictated by the development plans seeking higher production and productivity, maintenance of these small and traditional techniques were somewhat overlooked. In parallel, the emigration and rural exodus accelerated the degradation process. Coupled with the abandon and the occurrence of heavy rainfall events, many units of these structures were damaged and/or completely washed away. A regained interest at many levels (e.g. decision making, research, farmers, NGO, international agencies and donors) has resulted since the mid 80s in reconsidering the role and the place of the traditional soil and water conservation (SWC) techniques in the national and regional agricultural development plans. On the other hand, the tremendous population growth and the rapid development of many water consuming sectors (e.g. tourism, industry) have resulted in an accelerated competition for the water resources. To face the challenging dilemma of increasing food production with less allocated water, the mobilisation of all available water resources and the improvement of the water use efficiency are inevitable (Kassah, 1994). In the dry regions, WH is considered among the excellent methods for reaching that objective (Shatanawi, 1995; Oweis *et al.*, 2001; Ben Mechlia and Ouessar, 2002). It is in this framework that the objective of this article is to review the various water harvesting techniques encountered in south-eastern Tunisia and to discuss some aspects of their future prospects.

2.2 Environment

2.2.1 Geographic situation

The region of south-eastern Tunisia consists of the following provinces; Gabès, Médenine and Tataouine. Those are also the names of the main cities. The mountain range of the Matmatas crosses from NNW to SSE, beginning some 50 km southwest of Gabès, ending near the Libyan capital Tripoli. The main geographical zones are Jerba and the Djeffara-Ouara in the northeast, the Matmatas and the Dahar in the centre, and the Oriental Erg in the Southwest.

2.2.2 Climate

The area may be subdivided into three main climatic zones, the coastal area and Jerba being arid (maritime), the southern half of the plain, the Matmatas being arid (continental) and the Erg being Saharan. The entire region is situated below the 250 mm isohyet. Local variations in every sub-region depend on altitude, latitude and proximity to the Mediterranean (Mzabi, 1988). Annual rainfall averages generally declines from north to south.

The wet season stretches out over the months of November, December, January and February, and the summer months (June-August) are nearly rainless. Rainfall is characterised by two unfavourable features: Its irregularity and the high intensities of the showers. The intensity of the showers may frequently reach values as high as 100 mm h^{-1} for 5 minutes, which indicates high erosivity and causes, especially on shallow soils, violent runoff.

The coldest months are those of December, January and February with occasional freezing (up to -3 °C). June-August is the warmest period of the year during which the temperature could reach as high as 48°C (in the shade). The temperature is affected by the proximity to the sea and the altitude.

The principal winds affecting the plain are: in winter the cool and humid eastern/north-eastern winds, and in summer the hot and dry south-eastern winds, called *Chhili or Guebli*. These winds accelerate evapotranspiration and provoke soil erosion. The windiest period is February to April, sometimes May. This coincides with the ripening stage of many fruit trees, and wind plays a major role in the distribution of diseases. The two major directions in the mountains are less well defined; North to East and South to North-north West. Active winds make up about 41% of all the wind. Wind is considered active when it's speed exceeds 3 m s^{-1}. From that speed on it can detach and transport soil particles. For Médenine, an average 54 days $year^{-1}$ of Sirocco were registered. In Gabès an average of 18 days $year^{-1}$ with active wind (speed >16 m s^{-1}) was measured (Floret and Pontanier, 1982).

For Gabès, the relative air humidity (at noon) in summer is superior to that in winter. The year average is 58% at noon and 67% at 18:00 h. In January these values are respectively 55% and 66%, in July 61% and 68%. With high temperature and low rainfall, the potential evapotranspiration (ETP) is very high. It reaches, for example, in Médenine, 1321 mm. The climatic water balance is almost negative around the year.

2.2.3 Geomorphology and geology

Principal elements in the relief of Southeastern Tunisia are the plateau of the Dahar, Jebel Matmata, the plain of Jeffara-Ouara and the Grand Erg Oriental (MEAT, 1998).
The Dahar forms the back of the cuesta and stretches out from the northwest to the southeast, flanking the mountain chain. It is a calcareous plateau of 400 to 600 m elevation, torn by numerous wadis flowing from the mountains to the grand erg (Karray, 1979). A layer of limestone covers sequential strata of marl and marl/lime, dating from the Cenomanian (Mzabi, 1988). The natural vegetation cover is made primarily of degraded arid rangelands species. Besides some rainfed farming and irrigation in the oases, livestock husbandry is the main agriculture activity. The Sahara, found in the most south-western part of the country, is a xeric zone colonised by sand dunes.

Crossing the region from the north-west to the south-east the range becomes less massive and is cut into a number of hills of an average height of 400 meters, whereas in the north altitudes reach 600 meters. This is called the Djebel. The structure of the relief is clearly visible because of the absence of soil and vegetation; many slopes are totally uncovered, by wind or water erosion (Mzabi, 1988).

The Jeffara and Ouara, which are large plains consisting of crusted quaternary deposits, stretch between the Matmata mountains, the littoral and the borders with Libya. At highest, it reaches an altitude of 100 meter above sea level, and it ends in the sea. It is a terrain inclined by wadis, which drain the mountain zone after having run a long distance under a rather flat slope. Under a cover of undulations and fractures, the substructures of the Trias submerge near Médenine, and near Tataouine. It generally concerns layers of sandstone, which have subject to either wind or water erosion. Everywhere these clayey sand formations are covered by Quaternary sediments/ calcareous or gypsic crusts (Mzabi, 1988).

The Grand Erg Oriental, the substructure of the Tunisian Erg, is covered by a calcareous stratum of the superior Cretaceous that disappears under dune formations in the west. The sand dune fields are formed by alignments of long stretched form, called *sif*. Their dominating direction is NE-SW. In this sea of sand hills of submerging limestone locally appear. They reach heights of 200 to 250 m and are called *gour*. Because of the precipitation being almost nil, the wind activities prevail (Mzabi, 1988).

2.2.4 Soils

The south of Tunisia is made of large morpho-pedologic entities where the parent material and the impacts of coastal and Saharan climates have been the determining factors in soil formation processes (Mtimet, 1999): The main soil groups are:

a) *Sols calcimagnésiques*: They are encountered mainly in the glacis of Jeffara and El Ouara plains and the Dahar plateau. In fact, calcareous crusts cover the plain of the Dahar and protect the glacis at the foothill of the Djebel. It may submerge; otherwise a thin layer of sandy soil covers it. The soils are poor of organic material (<1%), nevertheless, they are used for arboriculture, mainly on the Djeffara, and in the vicinities of population dwellings.
b) *Sols isohumiques* (siérozems): They are found mainly in the loess deposits areas (Matmata, Béni Khédache). They are developed on a parent material with eolian origin that has been subject to heavy weathering and pedogenesis action (calcareous accumulations) during the medium and recent Quaternary periods (Mtimet, 1983). They are deep soils that occupy generally the slopes, the valleys, the large depressions of Tamezrat, Techine, Béni Khédache and Béni Zeltan and the surrounding areas. They have medium texture with fine sand and coarse silt. It is on these soils where the majority of *jessours* have been first installed.
c) *Sols salsodiques/halomorphes* (solontchak, solonetz): They are found in large depressions *(chotts)* and in *sebkhats* and *garaas* which form the outlets of numerous watersheds (Mtimet, 1999). They occupy large areas with saline crust during the dry periods or marshy lands with surface water table during the rainy periods. Gypsum accumulations could be encountered at a depth of 40 to 60 cm. The neighbouring areas of these units are generally colonised by wind accumulations *(nebkhas)* with halophyte vegetation used for camel grazing.
d) *Sols peu évolués d'apport* (fluvisols): They are considered among the best fertile soils in this region (Mtimet, 1999). They are made of water and wind erosion deposit materials. They are deep soils (> 1.5 m) with sandy loam to sandy texture. The organic matter could be higher than 0.5% and gypsum accumulations could be encountered at a depth of 40 to 60 cm. In the oasis, they show some aspects of salinity and water logging.
e) *Sols minéraux bruts:* They are soils having more than 70% of coarse materials (colluviums and alluviums). They are subject to fluvial weathering and wind deflation. They cover most of the Dahar plateau and the slopes of the bordering links as well as the bed bottoms of wadis (Mtimet, 1999).

2.2.5 Hydrogeology

Two main watertables can be distinguished in the south of Tunisia. The *Complexe Terminal (CT)*, under the Dahar and stretching out (mainly) into Algeria, and the *Continental Intercalaire (CI)*, under the Grand Erg Oriental/Occidental. A third one, the aquifer of Djeffara, may be distinguished, but it is essentially fed by the CI. The CT can be divided into two entities: the Nefzaoua (calcareous Senonien) and the Djérid (sandy Pontien inférieur). Depths in Tunisia are 100 to 300 m for the Nefzaoua, and 200 to 600 m for the Djérid. It is exploited intensively in the regions of Tozeur and Kébili. The CT stretches out over a surface of 600,000 km^2 under the Dahar, the CI and a big part of the Sahara Desert. Its depths vary between 1000 and 2000 m. It provides at some locations artesian water under high pressure and with high temperatures. The Djeffara aquifer is situated at the coastal plain and its depths are between 100 and 300 m. Apart from the CI it is also fed by infiltration in the mountains of Matmata. The aquifer is overexploited, especially at the level of Zeuss-Koutine.

2.3 Water harvesting systems

2.3.1 An Overview

El Amami (1982) made a comprehensive survey of the traditional hydraulic works in the Maghreb countries. This document, written in Arabic, was followed by a second document on Tunisia, in French (El Amami, 1984). These manuscripts cover all local techniques used for small-scale irrigation in North Africa, particularly Tunisia. The English term 'water harvesting' (WH) was not specifically used to describe the indigenous systems of runoff water capture and use. Actually, this term has been introduced only recently in the North African countries that are under the influence of the French language. Used terminology refers to water harvesting techniques (WHT) as 'small hydraulic structures or systems'. In any case, the described techniques exhibit the typical three main characteristics that were listed by Boers and Ben-Asher (1982), i.e.; i) they are applied in arid and semi-arid regions, ii) they depend upon local water, and iii) they are relatively small scale operations. El Amami's fundamental work (1982, 1984) has triggered an increased awareness of the potential of indigenous technologies for drought mitigation. Since then there have been a large number of studies on the methods used to induce, collect, store, and conserve local surface runoff for agriculture in arid and semi arid regions. Also, Ennabli (1993) and Ben Mechlia and Ouessar (2002) more recently presented a compilation of the same techniques.

The main water harvesting techniques encountered in this area (Figure 2.1) could be subdivided into three major groups: i) runoff water harvesting that makes use of runoff as it is collected, thus, eliminating the storage requirement. Among these are the related micro-catchment techniques like jessour; ii) floodwater harvesting and spreading or spate irrigation with diversion dikes called mgoud; and iii) runoff water collection and storage in reservoirs of variable capacities for drinking, animal watering and irrigation purposes.

Figure 2.2 shows the results of the implementation of the national strategies for soil conservation and water resources development for the decade 1990-2000 (Min. Agr., 1990a).

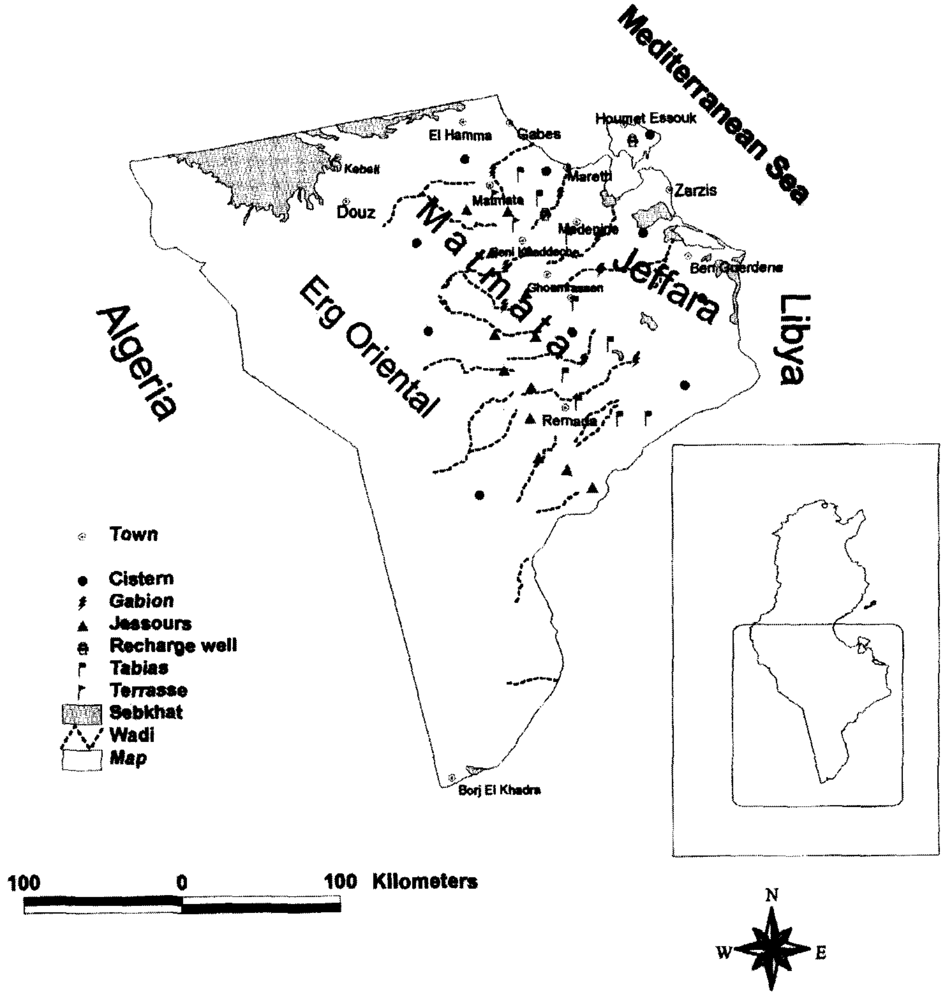

Figure 2.1 *Geographical distribution of water harvesting techniques in southeastern Tunisia.*

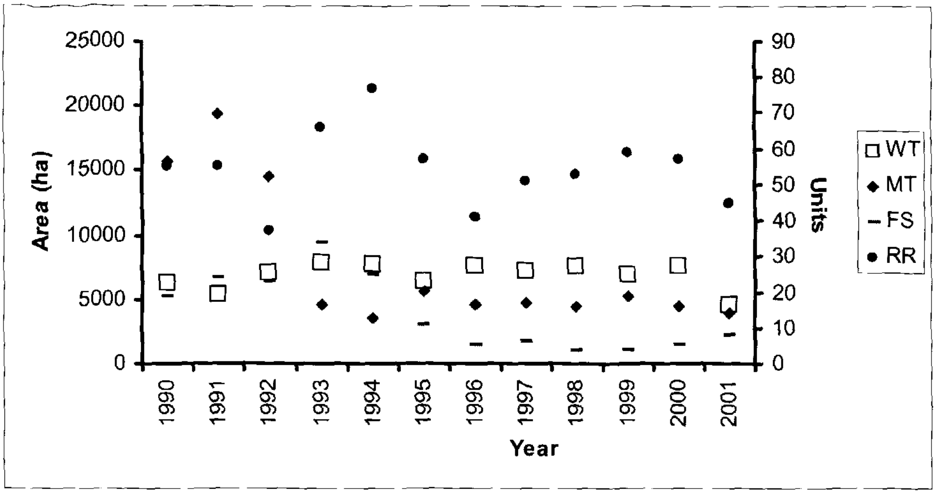

Figure 2.2 *Soil and water conservation works undertaken in the south eastern provinces from 1990-2000 (Min. Agr., 2001): WT: watershed treatment (ha), MT: maintenance (ha), FS: flood spreading (units), RR: recharge structures (units).*

2.3.2 Jessour

This old runoff water harvesting technique is widely practised in the arid highlands (Figure 2.1), dominated by the outcropping of calcareous formations and depositions of quaternary calcareous silt (loess). Average annual rainfall ranges from 100 to 200 mm but extremes of 80 and 700 mm have been observed. This technique has already been described in details in the manuscript written by Abi El Abbes (who died in 1110), cited by Ben Ouezdou *et al.* (1999). About 400,000 ha are covered by jessour, particularly in the Matmata mountainous range (El Amami, 1984).

Arranged in the form of a gradoni, the jessour generally occupy the runoff watercourses (*talwegs*). In fact, the jessour is the plural of a *jesr*, which is a hydraulic unit, made of three components: the impluvium, the terrace and the dyke (Photo 3.). The impluvium or the catchment is the area destined for collecting and conveying of runoff water. The natural water dividing line bounds it. Each unit has its own impluvium, but it can also receive the excess water from upstream units. The terrace or the cropping zone is the area where farming is practised. It is formed progressively by the decantation of the carried sediments. An artificial soil will be then created which can reach up to 5 m depth close to the dyke. Generally, fruit trees (e.g., olive, fig, almond, and date palm), legumes (e.g., pea, chickpeas, lentil, and faba bean) and barley and wheat are cultivated.

The dyke (*tabia, sed, katra*) is a barrier destined to block the sediments and runoff waters. Its body is made of earth equipped with a central and/or lateral spillway (*masref* and *manfes*) and one or two abutments (*ktef*), assuring the evacuation of the excess water. It has a trapezoidal shape (length: 15-50 m, width: 1-4 m, height: 2-5 m). In the old units, the dyke is consolidated with a coating of dry stones to overcome the wave impact on the front and the regressive erosion on the back. The spillway is made of well-arranged stones in the form of stairs to break down the kinetic energy of the overflow. The runoff/cultivated area ratio is estimated to be around five (El Amami, 1984), although higher values could be encountered (Chahbani, 1990; 1996).

Though this technique was developed for the production of various agricultural commodities, it is now playing three additional roles: i) water table recharge via runoff water infiltration in the terraces; ii) flood control and therefore protection of infrastructures and towns installed downstream and; iii) wind erosion control by blocking the sediments from reaching the plains where the wind is very active.

In spite of its importance, this technique is facing problems due to the lack of adequate maintenance as a consequence of socio-economic changes. Emigration and non-agricultural activities play an important role in income formation in the region. As the share of agriculture in family earning becomes very low there is a non-utilisation of lands by farmers leading to a progressive abandonment of jessour farming in the mountains and to the establishment of tree crops and cereals in the downstream zone, at the expense of the best rangeland. The abandonment of jessour agriculture is propelled by the reduction of community cohesion, which makes the necessary integrated and simultaneous treatment of an entire runoff unit more and more difficult, and the need for adequate mechanised construction of terraces, which becomes extremely expensive when undertaken by individual farmers.

Recent works addressed some solutions (pipe outlet spillway, drainage float, etc.) to protect the existing structures (Chahbani, 1990; 1996; 1997). Other studies have addressed the improvement of the geotechnical properties of the earthen dikes constructed by machines (Mtimet, 1992; Mellouli, 1996; Raboudi and Ouessar, 1999). It has also been reported that the management systems could be adapted to the new established social and economical context by the formation of watershed associations and co-operatives (Laffat *et al.*, 1997) or by intensification applying supplemental or limited irrigation using the cistern water (Chahbani, 2000).

2.3.3 Tabia

This technique is a replica of the jessour system constructed in the foothill and piedmont areas. So, it is considered as a relatively new technique developed by the mountain dwellers that migrated to the neighbouring plains. Alaya *et al.* (1993) reported that some ancient remnants of tabias were found in the region of Gafsa. However, this system has been adopted in neighbouring foothills and plains of central and south-eastern regions (Jeffara) of the country following the transformation of pasture lands to cultivated fields (Photo 4).

The tabia is a runoff WHT widely practised in central Tunisia. Tabias are usually installed on the piedmont areas where the slope does not exceed 3 % with relatively deep soils. It has the same components as jessours: a dyke (50-150 m length, 1-1.5 m height), a spillway (central and/or lateral) and an impluvium. The impluvium/cropped area ratios vary from 6 to 20. The differences between the tabias and jessour are the two additional lateral bunds (up to 30 m long) and sometimes a small flood diversion dyke (mgoud) (Alaya *et al.*, 1993). Fruit trees and annual crops are commonly grown. This system has been adopted in neighbouring foothills and plains of south eastern regions (Jeffara) following the transformation of pasture lands to cultivated fields (Figure 2.1). Besides their water harvesting qualities, tabias have also positive effects on soil erosion control and on groundwater recharge.

2.3.4 Floodwater harvesting

Floodwater harvesting systems are based on the principle of diverting the total or a portion of the floodwater carried by wadis to the neighbouring cultivated fields, in the form of natural irrigation. The remnants and some units still in function are found in the region. It seems that this technique has been practised since the Roman and even the pre-Roman times. However, El Amami (1984) believes that the arrival of the Arabs, who imported with them the immense experience of Yemen, was behind the adoption and the perfection of this technique at large scale.

In general, the artificial flood-spreading system has three components namely: the diversion dam, the distribution network, and the cropping fields. The diversion dam is normally made of earth and it acts as a fuse by breaking down in case of very intense floods. Recently, the gabion and reinforced concrete are becoming widely used. The network is made of open trapezoidal canals with decreasing sections when going downstream. As in irrigation networks, it consists of primary, secondary, tertiary, etc. canals. The slope is normally gentle, except at the partition points in order to avoid the sedimentation and the silting up of the network. However, the curing should be done at least once a year in summer. The fields are generally flat with rectangular form and delimited by an earth embankment to retain up to 1 m water. Crops that are grown on spate irrigation are mainly cereals, fruit trees, spices, and legumes.

For the natural spreading systems there is no need for the construction of diversion structures. It is a small catchment water harvesting procedure, whereby the gullies coming out of the neighbouring mountains (alluvial fans) feed directly the fields downhill. For example, *Mbazaat, Chereb* are wadi cropping systems generally used for cereal cultivation.

The flood-spreading techniques are very efficient for flood control and ground water table recharge especially in areas where piezometric level decline becomes increasingly a major concern with the development of irrigated fields on pumping wells (Yahyaoui and Ouessar, 2000). It is estimated that the spreading of runoff waters could mobilise as much as 25 million m^3 yr^{-1} (Mamou, 1997). In fact, this technique has been widely adopted in central as well as in southern Tunisia within the framework of the national strategy for water resources mobilisation (Min. Agr., 1990a; b).

2.3.5 Recharge wells

When the permeability of the underlying bedrock is judged to be very low, casting tubes could be drilled in to enhance the infiltration of runoff water to the water table (Photo 5). This technique has been first tried for the replenishment of the Zeuss-Koutine aquifer. It has been found to be very effective for improving the water level and salinity (Yahyaoui, 1997; Yahyaoui and Ouessar, 2000). It has been already extended to other areas (Jerba e.g.)

2.3.6 Terraces

Like in other regions of the country (e.g. Raf Raf) and the world, they are constructed on steep slopes. They are formed of small retaining walls made of rocks to slow down the flow of water and control erosion (Oweis *et al.*, 2001). It seems that this technique is the oldest adopted WHT in the area. However, they are completely abandoned and only some remnants are still found in the upper extreme area of Oued Koutine. Nevertheless, they have been recently readopted for small-scale afforestation works in the mountain ranges of Matmata.

2.3.7. *Cisterns*

Cisterns were traditionally used to provide drinking water. Runoff water is collected and stored in stone-faced underground small or large size cisterns, called *majel* and *feskia*. It is estimated by Ennabli (1993) that a tank of 35 m^3 capacity can meet the annual water needs of a family and its livestock. Small private or communal cisterns (5 to 200 m^3) and big cisterns (up to 70,000 m^3) are found throughout the water deficient zone under the 400 mm isohyet (Figure 2.1).

Basically, a cistern is a hole dug in the ground with gypsum or concrete coating to avoid vertical and lateral infiltration. Each unit is made of three main parts, the impluvium, the sediment settlement basin, and the storage reservoir. The impluvium is a sloping piece of land delimited by a diversion channel (*hammala*). In the flat areas, where it is possible also to exploit the floods via a diversion dyke, one also finds artificially paved runoff areas. A small basin before the entrance of the cistern allows the sedimentation of runoff loads. It improves the stored water quality and contributes to the reduction of maintenance costs. Big cisterns have, in addition to the storage compartment, a pumping reservoir from which water is drawn.

Ennabli (1993) claimed that this technique has been used during the pre-Roman and Roman eras for the collection and distribution of spring waters. Carthage received its drinking water from the Djebel Zaghouan via an aqueduct of 50 km, collected in a cistern of 50,000 m^3. The same procedure was also applied in other big towns such as Kef, Sbeitla, Tebourba, and Sousse. The collection of rainfall water accelerated with the arrival of the Arabs. More than 200 big cisterns are found in the central region of the country. The most famous one is that of Aghlabit in Kairouan, which was built in the nineteenth century, with a total capacity of 58,000 m^3. The use of cisterns also contributed to the development of large-scale livestock husbandry in areas where groundwater is not available because of quantity or quality constraints. It was estimated that 10 to 16 million m^3 yr^{-1} could be mobilised by this type of hydraulic infrastructure (Ennabli, 1993). Nasr (1993) reported that in the rangelands of Dahar, selling of cistern water is a widespread and attractive practice, especially during summer periods.

While studying a micro-catchment in the region of Beni Khedache, Sghaier and Chahbani (2001) found that the cistern water is not fully exploited. Through a cost benefit analysis simulation, they showed that the stored water in cisterns has a high potential for improving the farming system and incomes of jessour-based agriculture by practising supplemental irrigation and/or small-scale full irrigation speculations under green houses.

2.4 Future prospects

Rainfed farming in south-eastern Tunisia represents and will remain an important component of the agricultural production system. Its productivity, however, is severely limited by chronic rainfall deficits. One way to support the sustainability of this vulnerable system is by increasing water supply. Water harvesting techniques are presently covering large areas and are providing efficient support to rainfed agriculture.

The WHT are well adapted to their physical and social environment. They are playing various roles; water supplementation, flooding prevention, water table recharge, water and wind erosion control, etc.

They represent an enriching factor to the hydraulic network of the country. They ensure the mobilisation of a non-negligible amount of water in areas where the classic hydraulic infrastructure (e.g. dams) can not be installed because of climatic (high evaporation, low precipitation), and economic constraints. It is a strategic role. In addition, the growing competition for water resources due to the development of the industry and tourism activities results in a decline of the water shares for the agricultural sector. This makes WH, among others, as a useful alternative to fill the deficit.

The improvement of the performances of WH structures requires a good knowledge of all components of each method. The hydro-morphology at different scales, depending on the adopted technique, should be addressed intensively. The various impacts of combining old with new introduced WHT should be assessed and evaluated especially now that the 1990-2000 strategy for water resources development and soil and water conservation has been implemented (Sghaier and Chahbani, 2001; Yahyaoui and Ouessar, 2000). Taking into consideration the local know-how, the management practices of these systems have to be adapted to the new social and economic context. This will ensure a sustainable agricultural development of the dry regions (Chahbani, 1997; Laffat *et al.*, 1997).

The use of newly developed technologies, such as remote sensing and geographical information systems (GIS) in research, planning and management of WH projects has to be intensified as well (Renard *et al.*, 1993; Ribeiro, 1996; Zolleweg *et al.*, 1996; Oweis *et al.*, 2001).

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3 UNE APPROCHE SUR LA COLLECTE D'EAU AU NIVEAU DU BASSIN VERSANT : LE CAS DU BASSIN TALKJOUNTE AU MAROC

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Abstract

The Talkjounte watershed is located in the Ida-ou-Zeddarh region, south of the western part of the 'Haut Atlas', and north-east of Taroudant township. It encompasses a total area of 292.2 km^2 and constitutes a sub-watershed within the large Souss river basin.

The inhabitants belong to the *chleuh* Berber group and do mainly live in the valleys, where they apply surface irrigation by using natural springs and traditional irrigation canals, called *seguia*. These can be subdivided in two categories:

- Seguias, that make use of seasonal flooding, derived from the streamflow of the Talkjounte wadi;
- Permanent seguias, that obtain their water from natural springs. The Sins and Tamazirt seguias belong to this category.

The population applies a rotation schedule that is called *tiremt* or *tawala.*

Apart from using these surface and resurfacing water sources, people in the Talemt zone also explore ground water resources by means of several wells with pumps.

The Imi El Khang dam, that retains the water from the watershed, does not contribute to the upstream agricultural water supply. The periodic water release is meant exclusively for restocking ground water resources in the Souss valley.

Keywords: watershed, seguias with seasonal flooding, permanent seguias, rotation schedules.

3.1 Introduction

Le bassin de Talkjounte constitue un modèle d'utilisation des terres semi-arides dans des conditions d'équilibre écologique naturel même si récemment, il s'est produit une exploitation accrue de ses ressources naturelles. En combinaison avec les dernières fluctuations climatiques, l'augmentation de la densité des populations et les évolutions sociales qui en ont résulté nécessitent de profondes réflexions sur la stratégie à suivre pour optimiser la productivité de ces écosystèmes tout en les préservant contre les menaces de dégradation. Dans un souci de recherche sur les modes et les systèmes appropriés d'exploitation des ressources naturelles, l'étude du bassin de Talkjounte s'est penchée:

a) sur la connaissance de paramètres physiques du milieu naturel qui vont permettre de dégager les tendances de leur évolution actuelle et leur impact sur la vie de l'homme
b) sur l'analyse des impacts et une évaluation économique de la technique d'irrigation traditionnelle par les séguias dans un contexte sud marocain de plus en plus aride.

3.2 Presentation du bassin

3.2.1 Géographie physique

Situé dans les régions montagneuses des Ida ou Zeddarh au sud du Haut Atlas occidental marocain, le bassin de Talkjounte d'une forme allongée du nord au sud s'étale sur une superficie de 292,2 km², au nord-est de la ville de Taroudant. C'est un dispositif qui fait partie du grand bassin hydrologique du Souss. La géométrie du bassin montre qu'il est assez ramassé, donc la concentration de l'écoulement est rapide vers les drains. L'Assif de Talkjounte, qui dévale du massif ancien de Tichka avec un cours N-S, forme un affluent rive droite de l'Oued Souss. Au Nord, la ligne de partage des eaux entre les bassins de Souss et de Haouz se présente sous forme d'un ensemble de crêtes culminant à plus de 3000 m d'altitude (p.e. Askawn 3078 m, Awlim 3043 m, Takoucht 3095 m, Flilis 3083 m).

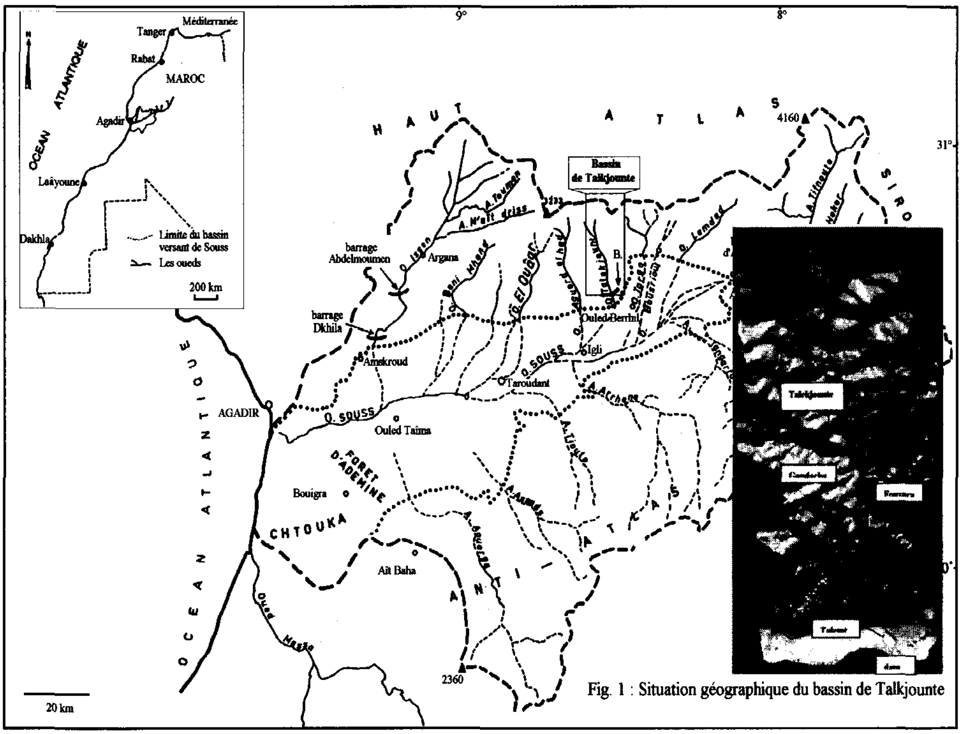

Fig. 1 : Situation géographique du bassin de Talkjounte

Figure 3.1 : *Situation géographique du bassin de Talkjounte.*

3.2.2 Géographie humaine

La population d'origine berbère chleuh parle le dialecte 'Tachelhit' (Ait Talemt, Ida ou Kais, Ida ou Mstoug) et se regroupe surtout dans les vallées où ils pratiquent l'agriculture de subsistance, l'élevage et l'arboriculture (e.a. oliviers et amandiers). La culture est irriguée traditionnellement et dans la mesure où les ressources en eau des cours d'eau ou des sources le permettent.

Depuis le 14ème siècle, des tribus arabes se sont installées dans le bas de la vallée et s'y sont fixées. Les populations berbères et arabes se sont brassées intensivement au cours des siècles pour aboutir à une certaine homogénéité : type, mœurs et bilinguisme arabe-berbère. Selon le dernier recensement officiel de la population et de l'habitat en 1994, la population totale du bassin s'élève à 12.181 habitants répartis en 1.782 foyers. Sur la base d'un taux d'accroissement annuel de 1.47 %, cette population serait aujourd'hui d'environ 13.147 habitants, soit une densité de 41 habitants au km². Cette population se regroupe dans près de 80 villages de tailles différentes. La localisation de ces villages suit les principaux cours d'eau.

Administrativement, le bassin est découpé en 3 communes rurales dont 2, Tigouga et Talkjounte, sont entièrement inclues dans le bassin, tandis que la troisième, Idaouguilal déborde sur la plaine vers le sud.

Tableau 3.1 *Répartition de la population du bassin*

Commune rurale	*Population en 1982*	*Population en 1994*	*Ménages en 1994*	*T.a.m.a [1] 82/94*	*Population en 1999 [1]*	*Habitant km⁻²*
Idaouguilal	-	1.790	250	1.05	1.884	35
Talekjounte	4.623	5.477	777	1.42	5.866	40
Tigouga	3.895	4.915	755	1.96	5.397	45
Total	-	12.182	1.782	1.47	13.147	41

Note 1: Chiffres estimés sur la base du taux d'accroissement moyen annuel (t.a.m.a) 1982/1994

3.2.3 Cadre géologique

Les formations géologiques qui affleurent dans le bassin peuvent être subdivisées en 3 formations principales :

a) Formation Précambrienne et Paléozoïque. Elle constitue le substratum hercynien d'âge Précambrien et Cambrien, et est représentée par le complexe cristallin granito-dioritique et gneissique du massif de Tichka, de type calédonien. Il occupe le haut bassin de Talkjounte. Et elle est représentée par l'ensemble schisto-calcaire du Cambrien et Cambro-Ordovicien. Il s'agit de schistes gris verdâtres imperméables d'âge (Acadien) riche en illites et chlorites, et des calcaires (Géorgien) dont la perméabilité permet à une partie de l'eau de ruissellement de s'infiltrer et de former des nappes souterraines profondes et captives.

b) *Formation Permo-Triasique.* C'est un ensemble pelitique et gréso-conglomératique avec des grès fins parfois conglomératiques en bancs décimétriques formant des escarpements. Cette formation est souvent coupée par des filons quartzitiques. Dans la zone de FOUZARA, les couches sont de direction N 45°E et de pendage 50° au SE. Cette formation peut être à l'origine d'une salinité des eaux qui la traverse.

c) *Formations post-Permo-Triasique.* Le Crétacé inférieur et de faciès gréseux et marnocalcaire présente un caractère lagunaire avec des niveaux à gypse (marnes rouges à gypses), et affleure sur les flans d'un synclinal orienté Nord-Sud (synclinal Talemt-Talkjounte). Au nord, les terrains du Crétacé sont bien visibles à Dar EL Qaïd et à TIBIT, au sud, ils forment les crêtes du Jbel Tadoust en structures monoclinales sub-verticales. Le Sénomanien marin présente des faciès marneux, marno-calcaires et calcaires à silex et conglomérats. La série Eocène est calcaire, marno-gréseuse et argileuse. Elle montre au sommet des niveaux gréseux rouges à galets. Elle affleure dans les flancs du synclinal

Talemt-Talkjounte. L'oligocène à caractère lacustre se présente en bancs carbonatés à silex et à quartz. Au pied du Jbel Tadoust, une série gréseuse très consolidée et des conglomérats hétérogènes mal triés se rattachent au Miopliocène. Les conglomérats grossiers pliovillafranchiens dominant la cuvette de Talkjounte sont bien individualisés dans le cône de Fouzara.

3.3 La couverture pédologique.

La majorité des sols du bassin de Talkjounte se développent sur un support d'altérités : produit d'altération météorique de roches formant le substrat. Ils sont variés et peuvent être repartis en :

a) *Sols minéraux bruts.* Caractérisés par une désagrégation météorique de la roche sous-jacente, ces sols sont du genre lithosols ou d'apport fluviatile.
b) *Sols peu évolués.* Ils se rencontrent sur des cônes de déjection et d'épandages provenant de la destruction des formations situées en aval.
c) *Sols isohumiques.* Ils représentent la majorité des sols bruns ou rouges de la cuvette de Talkjounte. Ils sont bien pénétrés par la matière organique.

3.4 Végétation et cultures

La végétation naturelle est dominée par l'arganeraie de montagne semi-aride d'importance fruitière, forestière et pastorale. L'arganier est indifférent à la nature lithologique des sols et se trouve sur des sols très variés.

Compte tenu de l'exiguïté du domaine cultivable, les terres irriguées sont intensivement exploitées : accumulation de deux campagnes agricoles en une seule année (céréales d'hiver puis céréales d'été). En plus, les agriculteurs pratiquent la culture étagée unissant sur la même parcelle les cultures annuelles et l'arboriculture. Aucune jachère n'est pratiquée et l'utilisation du fumier est impérative pour éviter l'épuisement des sols. L'assolement principal alterne les cultures d 'hiver (blé et orge)et celles du printemps et d'été (maïs).

Cette production est complétée par des légumes dans des proportions variables (oignons, navets, carottes, etc.). La rotation type est : orge / maïs ou bien blé / maïs. Cet ordre connaît aujourd'hui un grand bouleversement lié à l'introduction de la luzerne et de l'élevage bovin. L'arboriculture semble bien négligée. L'arbre ne fait l'objet ni de taille, ni de greffe, ni de fumure ; seule l'irrigation distingue les arbres fruitiers des arbres forestiers.

Malgré cette diversité apparente, le système de cultures du bassin accorde encore la priorité aux céréales, signe d'une économie de subsistance où la part des produits commercialisés est encore réduite : seuls certains produits de l'arboriculture tels que les amandes, les noix, les olives et les produits du caroubier font l'objet de vente dans le souk local ou dans la plaine.

Cette gamme de production bien que diversifiée reste pauvre et le revenu médiocre. Depuis longtemps déjà la nécessité d'un complément aux maigres ressources locales s'impose. Aussi la population du bassin a-t-elle recours à l'élevage entièrement intégré à l'agriculture et à l'émigration, devenue la principale source de revenus pour beaucoup de familles.

Tableau 3.2 *Cultures et superficies cultivées*

Cultures	*Superficie en hectare*	*Pourcentage*
Blé	300	34,3 %
Orge	500	57,2 %
Fève	60	6,9 %
Légumes	10	1,1 %
Autres (c.a. mais)	4	0,4 %
Total	874	100 %

3.5 Morphologie

Les zones fortement pentées du bassin sont marquées par une intense activité de l'érosion (par exemple : destruction des affleurements, creusement, glacis d'érosion), par une grande capacité de transport des ruissellements et par l'accumulation, à l'aval, de débris grossiers remaniés.

Le plateau de Tichka qui est élevé à plus de 3000 m forme les reliefs qui limitent le bassin au nord. Au sud, il s'effondre en donnant naissance à des falaises parfois vertigineuses et à des éboulis dont les pentes élevées (33%) contrastent nettement avec les replats qu'ils surplombent. Ces derniers peuvent correspondre à des glacis d'accumulation d'origine alluviale de faible épaisseur situés en bordure de chenaux (ex. replat de Godacha).

L'érosion différentielle met en relief les bancs durs (granite, calcaire, grès) et creuse les niveaux les plus tendres (schiste, marne, argile) taillant remarquablement des ensembles où apparaissent plissements, accidents, etc. Aux pieds de ces reliefs, peuvent se développer des petits glacis de versant ou des épandages en lambeaux étagés de pente faible qui traduisent sans doute des pulsations climatiques pluviales.

3.6 Ressources en Eau

3.6.1 Hydrologie

L'Assif de Talkjounte constitue l'un des plus grands confluents de l'oued Souss. Il prend naissance dans le haut massif de Tichka (versant méridional de la chaîne haute atlasique) et coule vers la plaine de Souss sur une longueur d'environ 30 km. Le cours principal, étroit en amont et large en aval, forme un système de drainage faiblement sinueux avec des passages quasiment rectilignes typiques des régions montagneuses fortement sollicitées par l'érosion. Il reçoit de très nombreux affluents dont les principaux sont celui de Talemet (10 km), celui de Fouzara (11 km), celui de Godacha (6 km).

3.6.2 Pluviométrie

Le climat du bassin de Talkjounte est marqué par une pluviosité faible avec une variabilité de précipitations accentuées et de répartitions annuelles aléatoires. Ceci constitue un frein au développement de l'agriculture et un facteur de dégradation du couvert végétal. Les pluies peuvent être classées en deux catégories :

a) soit des pluies de faible importance qui tombent en automne et au printemps sous forme d'averses ou de neiges sur les sommets. Ces chutes assurent les besoins en eaux (pour consommation, irrigation, couvert végétal, etc.) jusqu'au mois de juin ;
b) soit des pluies à caractère orageux favorisant une rapide concentration du ruissellement et de l'érosion avec parfois destruction de cultures.

Pendant la saison chaude (juin - septembre), l'assèchement des oueds et de certains points d'eau, l'abaissement des nappes aquifères provoquent des conséquences négatives sur la vie humaine en général.

Tableau 3.3 *Paramètres des pluies mensuelles des six dernières années (1995-2000) dans le bassin de Talkjounte*

	Sept	*Oct.*	*Nov.*	*Dec.*	*Janv*	*Fev.*	*Mars*	*Avril*	*Mai*	*Juin*	*Juill.*	*Août*	*An*
Moy.	3	24	34	64	67	35	85	11	6	7	0	2	337
% an	1	7	10	19	20	10	25	3	2	2	0	1	100
Max.	9	89	66	154	201	112	200	55	21	40	0	10	745
Min.	1	0	0	1	0	0	36	0	0	0	0	0	118
Ec.typ	3	31.5	25	66	71	41	57	21	8	17	0	0	215
C.Var	85	129	74	104	106	117	67	185	128	240	0	20	64

Il existe une contribution effective des eaux de Talkjounte à l'alimentation du système multicouche de la nappe libre de Souss. L'aquifère de Talkjounte est contenue en amont dans des formations calcaires paléozoïques. Les eaux de surface sont peu minéralisées à faciès bicarbonaté calcique voire calco-magnésien (substrat calcaire, schisteux ou gréseux).

En aval du bassin, l'aquifère est contenue dans les formations gréso-conglomératiques du remplissage plio-quaternaire. C'est à ce niveau qu'elle participe par des sous écoulements ou des infiltrations des eaux de l'oued (drainante ascendante) à la recharge de la nappe de Souss.

Le lit actuel de l'Assif Talkjounte coïncide vraisemblablement avec l'axe principal de drainage de l'aquifère puisqu'on note tout au long du tracé des résurgences multiples dont certaines ne tarissent pas même en période estivale (source du Khmis Talkjounte). Les relations hydrodynamiques avec les aquifères de Souss seraient permises grâce à la structure faillée du synclinal crétacé-éocène. Ce dernier constitue le substratum des réservoirs des eaux souterraines.

3.6.3 Le Barrage

Le barrage d'Imi El Kheng est implanté sur la cluse de Tadouste dans une démarche rationnelle de gestion et de contrôle des ressources d'eau (Photo 8). L'essentiel de l'eau est destiné à la recharge des nappes souterraines. Par conséquent, des efforts sont demandés pour que les agriculteurs des terres voisines puissent bénéficier de ces eaux. Leurs principales caractéristiques sont données dans le tableau ci-dessous :

Tableau 3.4 *Fiche synoptique du barrage d'Imi El Kheng (Direction de la recherche hydraulique, 1999, inédit)*

Barrage de Talkjounte	*Caractéristiques*
Bassin versant	Superficie de 292 km^2
Apport d'eau moyen	12 millions de m^3
Crues	316 à 1285 $m^3 s^{-1}$, soit un volume de 1,9 à 6 Mm^3
Aire du plan d'eau en retenue normale	165 ha
Aire du plan d'eau en période de hautes eaux	265 ha
Type de barrage	Barrage poids en BCR à 2 systèmes de vidange
Profondeur	41,5 m
Longueur de crête	170 m
Evacuation de crue	1300 $m^3 s^{-1}$
Coût global	42 Millions Dirham

3.7 Système d'utilisation du sol et de l'eau

3.7.1 Occupation du sol

La carte d'utilisation du sol permet de distinguer :

- La partie Nord où l'occupation du sol se résume à la pratique de l'élevage ovin et surtout caprin. Les terres relèvent du régime collectif des tribus en place, mais l'accès est ouvert à l'ensemble du voisinage.
- La partie sud est marquée par la présence de la forêt d'arganier dont le système d'exploitation repose sur : l'utilisation des produits sylvicoles (bois de chauffe, noix d'argan, etc.), la mise en culture exclusivement par des cultures annuelles sous pluie (céréales) et la pratique de l'élevage. Cette forêt est de statut domanial mais la population détient un droit d'usage.

La partie axiale du bassin est formée par les vallées des principaux cours d'eau : Tigouga et Talkjounte avec une occupation du sol très dense :

- Polyculture irriguée et étagée : palmier, olivier et arbres fruitiers divers.
- Arboriculture à dominant amandier et noyer en particulier dans le haut bassin. Dans cette partie, le statut privé des terres ou le *melk* est prédominant.

3.7.2 Utilisation de l'eau et irrigation

L'agriculture irriguée tient une place particulière; elle est le pilier de l'économie locale et rythme la vie des gens aussi bien par l'aménagement des terres irriguées que par la gestion de l'eau et du réseau d'irrigation.

Les secteurs irrigués sont localisés essentiellement au sud où les terres en terrasses sont relativement larges et basses sur des cônes aplatis. Chaque canal d'irrigation dit *targa* ou *seguia*, forme un périmètre géré par une des nombreuses communautés villageoises. La photo 6 montre le système des seguias. Le régime d'irrigation est libre en hiver. Mais, dès que l'eau commence à se faire rare, au printemps et en été, les villageois pratiquent un système de tours d'eau et chaque canal à son propre tour d'eau pendant 7,10 ou 15 jours. Chaque journée d'eau est elle-même décomposée en un certain nombre d'unités ou durée d'écoulement pendant laquelle chacun a le droit de disposer de l'eau de la seguia.

A coté de ce secteur principal basé sur l 'utilisation des eaux de surface, un secteur faisant recours aux eaux souterraines se situe dans la partie sud-ouest, le long de l'oued Talamt. Le pompage prend progressivement de l'ampleur grâce à l 'utilisation d'une motopompe (Photo 7).

3.7.3 Gestion de l'eau et organisation de l'irrigation.

Le caractère de l'écoulement des seguias, saisonnier ou permanent, loin d'être une simple donnée physique s'implique pleinement dans le domaine de la gestion de l'eau, de l'organisation de l'irrigation et détermine même, dans le cas présent, le statut juridique de l'eau et le type de distribution qui en découle.

Les seguias de crue, le statut collectif de l'eau

Dans les seguias de ce type, qui sont de loin les plus nombreuses, le statut de l'eau est collectif : elle fait partie intégrante de la terre qu'elle irrigue. Autrement dit, toute transaction de vente, de location ou de don sur le sol porte également sur l'eau qui l'irrigue.

Toutes les parcelles situées dans une seguia de ce type ont droit à une quantité d'eau dont l'importance est, en principe, proportionnelle à l'importance de la surface de chaque parcelle par rapport à la surface totale du secteur desservi. Cette quantité d'eau se situe dans un tour d'eau correspondant à une rotation de la seguia entre les différentes parcelles dans l'ordre de leur succession topographique de l'amont vers l'aval ou l'inverse.

En considérant le caractère saisonnier et irrégulier de l'irrigation dans ce type de seguia et, en conséquence, la difficulté de collecter des informations relatives aux cultures pratiquées, notamment au cours d'une période de sécheresse comme l'année en cours, nous avons jugé préférable de concentrer les observations sur les seguias permanentes : Tamazirt et Sins.

Dans les seguias de résurgence, peu nombreuses, relevant de cette catégorie, le statut de l'eau est propriété privée ('melk') indépendante de celle du sol. En d'autres termes l'eau peut être vendue, louée ou cédée à part.

Le processus de distribution consiste à livrer une part d'eau à un individu qui en devient ainsi propriétaire, indépendamment de l'importance de sa propriété foncière. Les parts d'eau sont proportionnelles, du moins à l'origine, à la contribution de chaque propriétaire dans les travaux de la construction ou du creusement de la seguia.

Tableau 3.5 *Organisation du tour d'eau de la seguia Ain Tamazirt*

Tour d'eau	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
Journées d'eau:	Nombre de propriétaires dans chaque journée d'eau :														
Jour	1	2	2	2	2	2	1	2	3	4	5	5	4	3	5
Nuit	1	1	1	1	1	1	2	3	2	4	6	6	3	3	6

Dans la seguia Ain Tamazirt, les parts d'eau des différents détenteurs se situent dans un tour d'eau de 15 jours. Cette durée est elle-même divisée en *tiram (tiremt)* ou journées d'eau correspondant à 12 heures aux équinoxes (un jour ou une nuit). Au total, cette seguia comporte donc 30 journées d'eau ; ensuite chaque *tiremt* ou journée d'eau est partagée entre un plus ou moins grand nombre de propriétaires qui jouissent ainsi de l'eau de la seguia, chaque fois que le tour de la journée d'eau arrive. Pour ce faire, la journée d'eau est elle-même divisée en sous-multiples se référant aujourd'hui aux heures et aux minutes.

De ce processus de distribution résulte ainsi une irrigation discontinue dans l'espace. La topographie ne comptant pour rien dans l'attribution de l'eau, celle-ci saute le vaste espace entre deux pour irriguer les parcelles d'un même ayant-droit généralement dispersées dans le secteur irrigué. Les droits d'eau ou les parts d'eau correspondent donc à un temps d'écoulement pendant lequel chacun ayant-droit dispose du débit de la seguia pour arroser ses terres là où elles se trouvent dans le secteur desservi.

Comme il apparaît sur le tableau, le tour d'eau ou la rotation de la seguia entre les différents propriétaires se fait sur 15 jours. Le nombre de propriétaires dans chaque journée d'eau est très inégal ; certaines journées correspondent à une seule part tandis que d'autres sont partagées en 6 parts d'eau. Cette répartition reflète en réalité l'inégale répartition de l'eau entre les propriétaires.

Tableau 3.6 *Catégories des parts d'eau par rapport aux propriétaires*

	Unités :	*Tours d'eau pour les différents propriétaires (les plus longues)*								
Catégories des parts d'eau	Heures et minutes	30	24	12	6	5 15	4 30	3 45	3	2 25
Effectif de propriétaires	Nombre	1	4	4	11	1	2	5	12	5
		Tours d'eau pour les différents propriétaires (les plus courtes)								
Catégories des parts d'eau	Heures et minutes	2	1 50	1 45	1 30	1	0 35	0 30		Total
Effectif de propriétaires	Nombre	1	8	1	11	1	3	2		72

Le tableau ci-dessus laisse voir les différentes catégories de parts d'eau reflétant l'inégale répartition de l'eau entre les propriétaires dans un rapport de 0,5 à 30 heures ou de 30 minutes à 30 heures. Encore faut-il rappeler qu'il s'agit là uniquement de 72 foyers propriétaires des eaux de la seguia permanente d'Ain Tamazirt.

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Photos of water harvesting techniques at the research sites


Photo 1."Gavias" water harvesting system on Fuertaventura, Canary Islands.

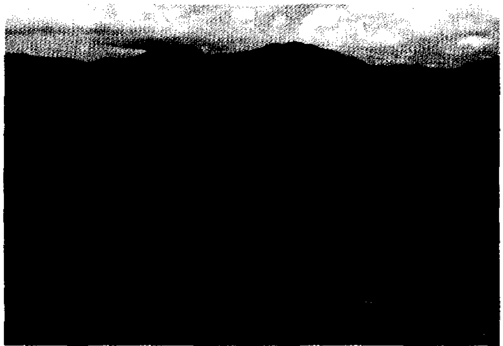
Photo 2.Natural arenados, La Geria, Lanzarote, Canary Islands.


Photo 3.Amrich jessr in Matmata mountains, Tunisia.

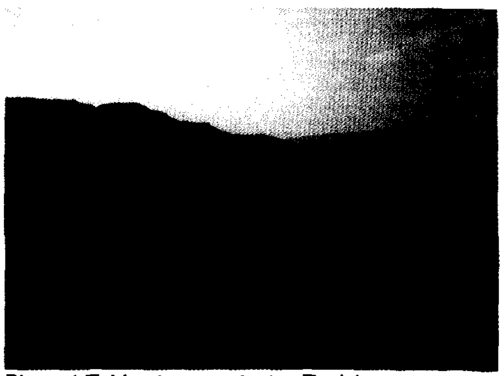
Photo 4.Tabia at research site, Tunisia.


Photo 5.Groundwater recharge structure, Tunisia.


Photo 6.Oued Talkjounte and seguia canal, Morocco.


Photo 7.Well in the Talkjounte valley, Morocco.


Photo 8.Hillside dam with lake, Morocco.

Part II :

Hydrological aspects of water harvesting techniques

4 RUNOFF HARVESTING SYSTEMS IN THE CANARIES

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Abstract

Soils in arid regions are characterised by a lack of water, a circumstance that acts as a barrier to dry crop farming. The islands of Fuerteventura and Lanzarote are among the most arid zones in Europe. The general climate features are as follows: extremely arid, annual rainfall of below 150 mm, potential evapotranspiration above 2,000 mm and average annual temperature around 20 °C. A traditional farming system, known locally as *gavia* (-water harvesting technique) has been developed in these islands, allowing a diverse and productive form of agriculture that uses no irrigation.

Monitoring of soil moisture in two field plots was conducted over a 3-year period. It was compared with an adjacent plot that received no runoff during the study period. Sampling was carried out once per month, every 10 cm to a depth of one metre, and moisture was measured using the gravimetric method. In both field plots, the differences between the runoff harvesting and the plots with no runoff is noteworthy. The gavias act as natural mulch and only the soils where the system is used had sufficient available water in the root zone to enable crops to be planted and achieve a level of production which would not be possible in the non-treated soils. The percentage of humidity is above the wilting point during the rainy seasons and for a few months subsequently. In the adjacent plot the humidity percentage remains below the wilting point year-round.

These differences in the soil moisture content affect the salinity and sodicity of the soils. Indeed, while natural soils adjacent to the gavias may be classified as saline-sodic, this problem is not present in the soils within the gavias. This trend in salinity and sodicity is the same in all the systems, in very different situations.

Thus, this system seems to be very efficient in reducing soil salinity and sodicity, even in the zones near the sea. Hence the interest in preserving this traditional agricultural system for the conservation of two valuable resources in the Canary Islands: water and soils. However though, the gavia system is in decline today. Its minor economic worth does not reflect its cultural, landscape and environmental importance.

Keywords: soil moisture, arid soils, dry farming, anthropic changes, runoff harvesting, gavia, water conservation, soil conservation, saline soils

4.1 Introduction

Runoff occurs as a result of intense rainfall and poor soil infiltration, characteristics that are very common in arid and semi-arid tropical regions (Reij *et al.*, 1988). Surface water can be harnessed for agricultural use if channelled and directed to cultivation plots surrounded by small walls. This traditional dryland farming system is known locally in the Canaries as gavias and dates back to the period of conquest by the Spaniards, although no exact date can be given (Roldán, 1968). Although present on other islands in the Canaries, where some remains can still be found, they are most widespread nowadays in Fuerteventura (Quirantes, 1981). It is estimated that an area of approximately 3,800 hectares is taken up by gavias (MAPA, 1989).

The most important crops grown are winter cereals. Although in terms of yield and economic worth the system's importance is negligible, its conservation and operation clearly play a major role in combating desertification, particularly in such an arid part. Indeed, the gavias are a system for soil and water conservation, as the present paper seeks to bring out.

4.2 Presentation of study zone and system

4.2.1. Area description

Our study was conducted in soils in Fuerteventura and Lanzarote (in the Canary Islands, Spain), that are located 115 km off the West Coast of Africa. These islands are among the most arid in the European Union with the following climate features: annual rainfall below 150 mm; torrential rain which falls very heavily and briefly; high potential evapotranspiration (in excess of 2,000 mm in an evaporimeter tank); a daily average of around 8 hours sunshine; annual average temperature of around 20 °C, with considerable differences between night and day; high relative air humidity (> 70%) and strong winds (Torres, 1995).

Rainfall events with an intensity up to 10mm in 24 hours represent 66.5% and 66% of total rainfall, respectively, whereas those with an intensity of over 50 mm in 24 hours represent just 0.6% and 0.7% of the total for each island (Marzol, 1988). Water resources are extremely limited and 90% of all water used comes from seawater desalination.

4.2.2 Description of the gavias system in the Canaries

The gavias system, which was designed to collect runoff in arid zones of the archipelago, has given rise to small-scale dryland farming. The gavias are located near flat zones, usually on foothills, and are oriented perpendicular to the steepest sloping area generating the runoff. They are frequently close to small watercourses, small ravines, from which runoff can be collected. The systems comprises cultivation plots, protection walls *(trastones),* runoff water entry *(torna),* excess water exit *(desagüe)* and a water channel *(caño)*

The plots are completely surrounded by earthen walls between 50-80 cm high, although sometimes these can be up to 1.25 metres. Water enters via an opening at ground level in the part that receives the runoff initially. This opening may simply be a lowering of the wall, a part made of stones and *aulagas* shrubs (*Launaea arborescens*) and even, on occasions, a cement and stone construction with a wooden gateway that is raised and lowered as required.

Excess water can be diverted to another gavia located lower down. This can be achieved by simply lowering the height of the protection walls, which can be reinforced with stones and cement. The height of this lowered part can be between 15-70 cm, but is most commonly 30 cm. The water outlet has to be at least twice as wide as the entrance so that the gavia can evacuate its water automatically without giving time for the wall to be damaged. In other cases, excess water is diverted towards a small ravine located to the side (Tascón, 1997). Where runoff water does not reach the gavia directly, water from nearby small ravines can be brought in using a rudimentary channel, consisting of just earth, or earth reinforced with stone or even cement.

Generally speaking, gavias are grouped in a terraced-like formation, known locally as a 'rose'. If the water intake exceeds the amount envisaged by the design, the walls can be severely damaged and considerable quantities of both water and soil are lost. The gavia system requires annual upkeep, for the most part rebuilding of walls and cleaning out the runoff channel structures. These jobs require considerable labour because they are, by necessity, manual and the plots are very small. The arrangement of the gavias rules out machinery in most cases. Without the work, the deterioration caused to the structures by runoff during heavy rain would be irreversible. The expression '*gavia bebida*' (literally 'imbued gavia') is used in Fuerteventura to denote cases where water has saturated and infiltrated the gavia.

Once the water has entered the system the soil is tilled to break the capillarity and conserve moisture (mulch effect), and then seeding takes place. The main traditional crops grown are winter cereals (wheat, barley, oats and corn), as well as lentils, chickpeas, and beans. Other crops, such as saffron and potatoes, are also grown, albeit to a lesser extent. The system can be viable in 5-6 years out of every 10, which is the usual frequency with which the gavias are filled.

4.2.2. Systems studied

Two systems with different characteristics were chosen, one on Fuerteventura (field-plot 1) and the second on Lanzarote (field-plot 2). In the latter case, there are very few hectares of farmland under this type of cultivation system.

Field-plot 1 is located on a north-eastern coastal plain in Fuerteventura, less than a kilometre from the coast. It comprises two terraced gavias with earthen walls, which receive runoff water channelled from an adjacent basin (Photo 1). The gavia is situated at the bottom of a watercourse, which has enabled it to accumulate large amounts of fine materials, giving it a depth of around a metre, compared to the 50 cm of neighbouring soils. The plains representative soils outside the gavia presented a petrocalcic horizon at about 50 cm depth, which prevented us from taking deeper samples of the adjacent natural soil (Fernández Caldas *et al*, 1987). The soil is highly carbonated and generally presents a balanced texture. Surface stoniness (with stones and basaltic and calcareous gravel) is high (80-90%), a circumstance that reduces erosive processes. Erosion is low and of the sheet type. Around 63 hectares of crops receive runoff water from a water basin of 1,079 ha. Hence the crop area/catchment area ratio is 1:17. The studied gavia measures 0.34 ha. The walls and the water outlet are 50 and 30 cm high respectively. Lentils and corn are normally grown. Two harvests were obtained during the study period.

Field-plot 2 is located in the central part of Lanzarote. It comprises a system of three gavias, which have been terraced using stone walls. The gavias receive runoff water channelled from a catchment area at the foot of a volcano (Guanapay Mountain). The natural soils adjacent to the gavia present a highly developed argillic horizon, with some carbonatation (Fernández Caldas *et al*, 1987). They are very prone to water erosion, with abundant gullies. Around 0.21 ha of crop-growing area receive water from 7.6 ha of catchment area, giving a ratio of 1:30. The most frequent crops are corn and barley. Planting took place twice during the study period.

4.3 Field and laboratory

For the monitoring of soil moisture, samples were taken over a period of three years, approximately once per month, every 10 cm to a depth of one metre both in the plot used for cultivation as well as in the one not used thus. Volumetric water content was calculated by the gravimetric method, taking into account apparent density.

To study salinity-sodicity characteristics a profile was studied out within the system and another in the adjacent natural soil. Samples were taken every 10 cm throughout the full depth of the soil.

Bulk samples were allowed to air-dry and the soil 2-mm mesh sieved for laboratory analysis. Retained moisture at 1500kPa was estimated by pressure-plate extraction, using a porous ceramic plate (USDA-NRCS, 1996).

Soil pH was measured in a 1:2.5 soil/water suspension. The electrical conductivity was measured in saturated paste (USDA-NRCS, 1996). The cation exchange capacity was determined after Bower *et al.* (1952). Exchangeable Na and K were extracted with a buffered neutral 1 M NH_4OAc solution, and Ca and Mg by 1 M NaOAc pH 8.2. Solution concentrations were determined by atomic absorption spectrophotometry. Particle size analysis (particles < 2mm) was determined after samples were dispersed in sodium hexametaphosphate solution and shaken on a horizontal reciprocating shaker for 12 h using the densimetric method (Day, 1965). Carbonate contents were determined according to Allison and Moodie (1965).

4.4 Results and discussion

A full weather station was available for field-plot 1, whereas for field-plot 2 rainfall data from a nearby station were used (Table 4.1).

Table 4.1 *Monthly and annual precipitation (mm) for the study area*

Period	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*Total*
Site 1 (1971-2001)	17.2	16.2	13.0	5.4	1.0	0.0	0.0	0.0	2.6	8.5	13.0	22.3	99.2
Standard deviation	27.2	24.3	14.2	9.1	2.7	0.1	0.1	0.0	4.3	14.9	17.2	27.3	51.4
Site 2 (1982-2000)	21.4	15.0	15.7	3.5	1.3	0.3	0.0	0.0	1.7	11.9	19.5	32.4	124.1
Standard deviation	17.8	23.7	14.5	6.2	1.7	0.8	0.0	0.0	2.4	14.8	23.6	34.4	66.9

Monthly and annual variations in rainfall are very high, with the bulk of the rain falling during autumn and winter. Maximum intensities (24 h.) recorded during the study period were 10.2 mm (5/12/98), 21.0 mm (12/1/99), 25.2 mm (13/1/99), and 60 mm (12/3/99) for the station on the island of Fuerteventura (site 1). For Lanzarote the highest daily rainfall recorded was 45.6 mm (5/12/98) and 23.2 mm (27/10/99).

Figures 4.1 and 4.2 show the accumulated water content in 100 cm of soil (gavia and no runoff) on each of the sampling dates, together with precipitation accumulated between sampling.

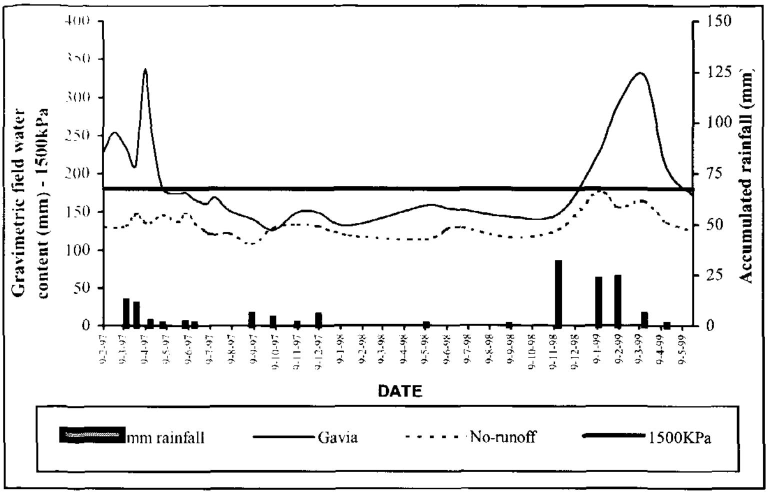

Figure 4.1. *Field-plot 1. Total gravimetric field and 1500 KPa water content in gavia and in no runoff. Effective soil depth:100cm.*

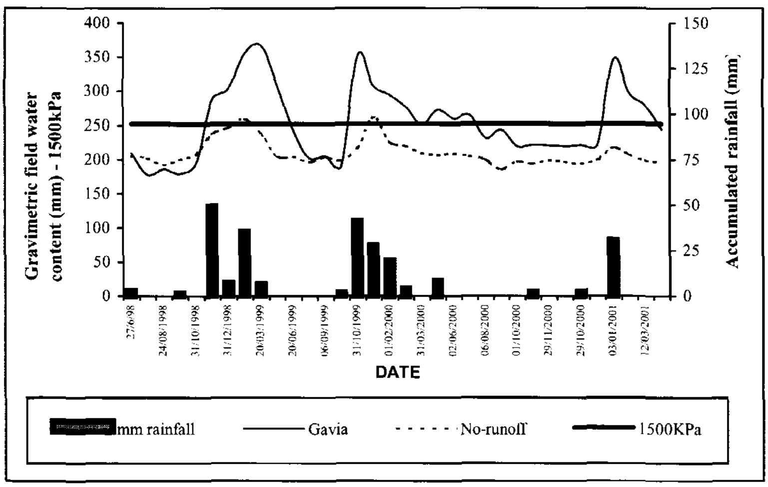

Figure 4.2 *Field-plot 2. Total gravimetric field and 1500 KPa water content in gavia and in no runoff. Effective soil depth:100cm.*

The gavias act as natural mulch. Only in the soils where the system is used was sufficient water available in the root zone to enable crops to be planted and achieve production levels which would be impossible to obtain in the non-treated soils. The percentage of water content was above the wilting point during the rainy seasons and some months afterwards. Differences in water content were noteworthy throughout the year. In the adjacent field-plot (no runoff) the percentage of water content remains below the wilting point throughout the year. The relationship between the accumulated water in the gavia system and in the non-gavia plot was 1.4 (field-plot 1) to 1.2 (field-plot 2).

The gavia soils are more alkalyne than the adjacent natural soils. Of the exchangeable cations, calcium and magnesium predominate in the former, unlike in their natural counterparts, where sodium is more important. The salinity results are shown in the figures 4.3 and 4.4. The behaviour is similar in the two systems, in that the gavia soils are non-saline and the adjacent natural soils are extremely saline.

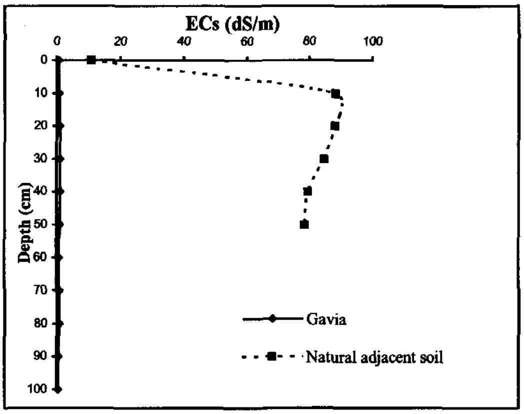

Figure 4.3 *Comparison of salinity in the gavia soil and in the natural adjacent soil in field-plot 1*

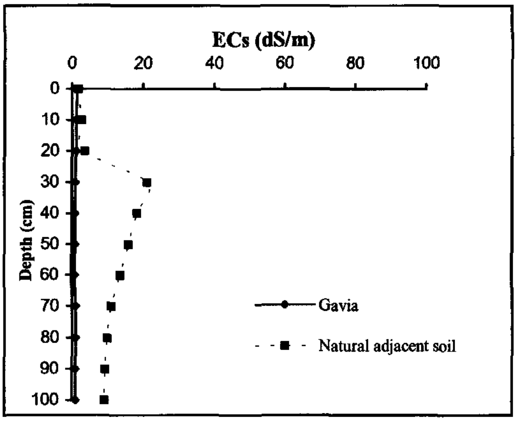

Figure 4.4 *Comparison of salinity in the gavia soil and in the natural adjacent soil in field-plot 2*

Regarding sodicity (Figures 4.5 and 4.6), as can be seen, the gavia soils cannot be considered sodic, unlike their non-covered counterparts, which are extremely sodic.

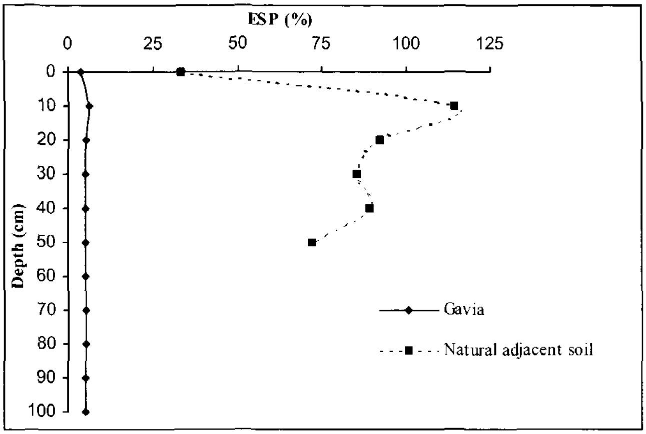

Figure 4.5 *Comparison of sodicity in the gavia soil and in the natural adjacent soil in field-plot 1*

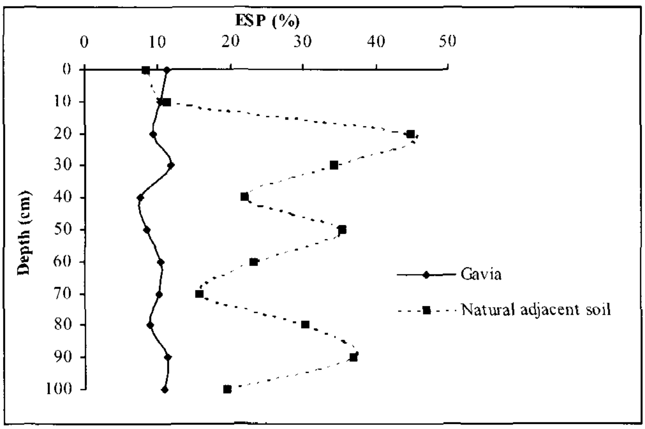

Figure 4.6 *Comparison of sodicity in the gavia soil and in the natural adjacent soil in field-plot 2*

The above tendencies, in the case both of salinity and sodicity, are seen in all the systems studied, despite their different situations. In the light of the results obtained, we can conclude that the gavias are a very effective system in arid regions because they reduce salinity and sodicity in soils, even those located very close to the sea. The washing effect of the system is spectacular, particularly in the case of the gavia situated just a few metres from the sea (field-plot 1).

In such extreme environmental conditions, without irrigation, no crops would be possible if these traditional farming systems did not exist. Gavias are today in decline as farming systems. Their economic worth falls considerably short of their cultural, landscape and environmental value.

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5 IMPACTS OF WATER HARVESTING TECHNIQUES ON SOIL AND WATER CONSERVATION AT FIELD AND SUB-CATCHMENT SCALE IN THE OUED OUM ZESSAR WATERSHED

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Abstract

As part of the WAHIA-project (impact assessment of water harvesting techniques) infiltration and runoff measurements were carried out at the impluvium of the Amrich jessr, situated in the Zeuss Koutine watershed (Tunisia). The results of these experiments were used as input data for the Sediment Transport Model (STM) in order to estimate the effect of water harvesting techniques (WHT) like the jessr on soil and water conservation.

Infiltration and runoff were measured by means of a small Kamphorst infiltrometer and a large field rainfall simulator. The results showed that the infiltration rate measured by the infiltrometer was about 3 times higher than with the field rainfall simulator. Probably the breaking of the surface seal during installation had a much larger impact on the infiltrometer measurements. The field rainfall simulator provided a better approximation of natural rainfall and prevents breaking of the sealed soil surface. Therefore the results of the field rainfall simulations were used to estimate infiltration and runoff. In order to assess the transport of sediment with runoff, a sediment transport equation was developed on the basis of the field rainfall simulation results, using the stream power concept.

The infiltration characteristic and the sediment transport function enabled to estimate runoff and erosion on an event basis. Several simulations were done for different rainfall events that occurred since April 1998. The simulation results indicated that during intense rainfall a lot of sediment and water are retained by the terrace of the jessr, preventing it from being transported downslope. Therefore, WHT like the jessr are important for soil and water conservation. Over a period of 3 years, rainfall and infiltration data were used to assess the water balance on the terrace of the jessr. The results showed that especially during dry years the impluvium of the jessr provides an important supplementary amount of water for the cultivation of olive trees. Furthermore it was estimated that the ratio 'area impluvium/area terrace' should be larger than 7.4 in order to provide, on average, sufficient water for olive cultivation, taking into account an average annual precipitation of 235 mm. If the ratio 'area impluvium/area terrace' is larger than 29, enough water is provided by the impluvium in 97 % of the years.

Keywords: Infiltration, erosion, water harvesting, water balance, evapotranspiration, jessr

5.1 Introduction

Arid zones are characterised by small, average annual rainfall amounts. However, very high rainfall intensities can occur, causing runoff and erosion on the hill slopes. In order to increase the amount of water available for crop production and cattle breeding, several types of water harvesting techniques (WHT) have been developed. In Tunisia, common WHT are jessour (singular: jessr), terraces, tabias, cisterns, gabions, recharge wells and mescats. A more detailed description of these WHT is given by Ouessar *et al.* in Chapter 2

The use of WHT is not only restricted to collecting water for agriculture. Runoff causes erosion of the fertile topsoil, resulting in soil degradation on site. Moreover, the eroded soil is transported towards the oueds, where it increases the risk of flooding in adjacent areas. WHT like jessour decrease the amount and velocity of the runoff water, and consequently reduce soil erosion. Moreover, part of the eroded soil is deposited on the terrace of the jessr, ameliorating the soil water storage capacity and resulting in higher soil fertility. The on site and off site benefits of WHT emphasise the need of restoring and maintaining these systems.

In order to be efficient, WHT should be constructed in proportion to the amount of water that can be expected during a rainfall event. Therefore, data are needed on rainfall, topography and soil characteristics like infiltration rate and water retention. However, in desert and arid areas the availability of these data is limited. The purpose of this study was to examine the impact of WHT like the jessr on erosion and water availability for crop production. Therefore, existing rainfall data were analysed and additional field measurements were done in a small sub-watershed in southern Tunisia.

5.2 Materials and methods

5.2.1. Study area

This study was carried out in the Oued Oum Zessar watershed, situated between Kébili, Gabès and Médenine in the southern part of Tunisia and having a surface area of 367 km^2. Within the watershed an ancient jessr at Amrich, located upstream of Oued Nagab, was chosen as an experimental site to assess runoff, erosion and the impact of the jessr on the water balance. A jessr is a WHT by which water coming from an impluvium is collected on a terrace surrounded by a dike (Figure 5.4). The terrace is used for crop cultivation; in the Amrich jessr 5 olive trees are grown on the terrace. The area of the terrace and impluvium are respectively 0.275 ha and 8 ha.

5.2.2. Field measurements

At Amrich the soil profile of the terrace was sampled at different depths (until 1.4 m) in order to determine the soil texture and the water retention curves. Soil texture data of the terrace are given in Table 5.1. Since April 1998 a tipping bucket raingauge (precision: 0.1 mm) was installed at El Bhayra and Chouamek to record rainfall intensities continuously. The weather station nearest to the Amrich site is Chouamek at 2 km distance. Daily rainfall data of the weather station at Béni Khedache were available over the period 1969 – 2000 (data of the years 1971 and 1991 were missing). Table 5.2 shows that during the period 1969 – 2000 the average monthly rainfall varies between 0 and 40 mm, with the driest period from June till August. The potential evapotranspiration (PET) was calculated by means of the Penman-Monteith method (Smith, 1991), using data of the meteorological station at Médenine. Over the period 1985-1995 average PET values were calculated per decade of days, setting the number of days per month equal to 30. The maximum crop evapotranspiration (ET_c) was calculated based on the PET values and the crop coefficient k_c. Values of k_c are based on data for olive trees given by Lelivelt (2001). In case the soil moisture content is insufficient to reach ET_c, the actual evapotranspiration (ET_a) will be lower than ET_c. To calculate the ET_a the equation of Rijtema and Aboukhaled (1975) was used, taking into account the fraction (p) of the total soil water content that is easy available for the olive trees. The rooting depth of the olive trees was assumed to be 1.4 m (Doorenbos and Kassam, 1979). Values of PET, ET_c, k_c and p are given in Table 5.2.

Table 5.1 *Soil characteristics at different depths in the soil profile of the terrace at the Amrich jessr (OM = organic matter, θ_{FC} = moisture content at field capacity (9.8 kPa), θ_{WP} = moisture content at wilting point (1554 kPa))*

Depth (m)	*0-2 µm ($g\ g^{-1}$)*	*2-50 µm ($g\ g^{-1}$)*	*50-2000 µm ($g\ g^{-1}$)*	*OM ($g\ kg^{-1}$)*	*$CaCO_3$ ($g\ kg^{-1}$)*	*θ_{FC} ($m^3\ m^{-3}$)*	*θ_{WP} ($m^3\ m^{-3}$)*
0-0.075	0.152	0.206	0.643	17.6	9.4	0.362	0.099
0.075-0.225	0.179	0.189	0.632	9.7	12.8	0.308	0.109
0.225-0.375	0.171	0.187	0.642	8.5	27.0	0.324	0.104
0.375-0.525	0.160	0.196	0.644	8.0	22.2	0.251	0.096
0.525-0.675	0.083	0.034	0.883	1.7	32.8	0.283	0.037
0.675-0.825	0.135	0.120	0.745	7.4	31.6	0.307	0.086
0.825-0.975	0.119	0.147	0.734	5.1	9.4	0.294	0.104
0.975-1.125	0.178	0.132	0.691	4.5	26.0	0.289	0.097
1.125-1.4	0.130	0.151	0.719	2.3	36.6	0.299	0.084

Table 5.2 *Average monthly rainfall (P), rainfall days (N), potential evapotranspiration (PET), maximum crop evapotranspiration (ET_c), crop coefficient (k_c) of olive trees and fraction (p) of the total water content that is easy available for olive trees*

Month	*P (mm)*	*N*	*PET (mm)*	*ET_c (mm)*	*k_c*	*p*
Jan	37.5	3.4	69.6	27.8	0.40	0.88
Feb	30.6	2.8	88.6	35.4	0.40	0.88
Mar	40.0	3.0	121.2	66.7	0.55	0.86
Apr	16.3	1.8	159.3	79.6	0.50	0.83
May	11.2	1.2	198.4	89.3	0.45	0.80
Jun	1.0	0.3	213.5	85.4	0.40	0.81
Jul	0.0	0.0	234.8	82.2	0.35	0.82
Aug	2.0	0.3	220.9	77.3	0.35	0.83
Sep	17.1	2.0	166.6	75.0	0.45	0.84
Oct	23.0	2.4	126.8	63.4	0.50	0.86
Nov	19.9	2.3	91.1	41.0	0.45	0.88
Dec	36.7	3.3	67.4	26.9	0.40	0.88

Because the number of rainfall events in arid environments is limited and shows a lot of variability, it was decided to determine runoff on an event basis, using the Time Compression Approximation (Ibrahim and Brutsaert, 1968). In order to apply this concept, infiltration data are needed. The soil infiltration characteristic was determined by means of two types of infiltration measurements carried out in the impluvium of the Amrich jessr: a small rainfall simulator (Kamphorst infiltrometer (Kamphorst, 1987)) and a large, mobile field rainfall simulator (sprinkler) (Figure 5.1). At the impluvium of Amrich three experiments have been carried out with the Kamphorst infiltrometer:

a) low initial soil moisture content (0.010 g g^{-1}), 10% stone cover, 16% slope.
b) high initial soil moisture content (0.104 g g^{-1}), 10% stone cover, 16% slope
c) high initial soil moisture content (0.121 g g^{-1}), 20% stone cover, 28% slope

A rainfall intensity of 200 mm h^{-1} was applied on a surface area of 0.25 × 0.25 m during a period of 800 to 900 s. Runoff was collected every minute.

The large field rainfall simulator was used for 6 runs on 3 different places at the impluvium of Amrich:

- plot 1: 50% stone coverage and 18% slope; one run at low (0.012 g g^{-1}) and one at high (0.067 g g^{-1}) initial soil moisture content
- plot 2: 80% stone coverage and 28% slope; one run at low (0.039 g g^{-1}) and one at high (0.178 g g^{-1}) initial soil moisture content
- plot 3: gully with 90% stone coverage and a 23% slope; one run at low (0.019 g g^{-1}) and one at high (0.16 g g^{-1}) initial soil moisture content

Plots 1 and 2 were situated near the spots where the infiltrometer experiments a, b and c were done. A rainfall intensity of 50 mm h^{-1} was applied on a surface area of 3×1 m. Runoff and sediment discharge were measured every minute. The rainfall simulation runs lasted for 360 to 900 minutes


Figure 5.1 *Mobile rainfall simulator (left) and Kamphorst infiltrometer (right) used in the Amrich jessr*

5.3 Results and discussion

5.3.1 Infiltration and runoff

The average cumulative infiltration values of the rainfall experiments carried out on plots 1 and 2 are presented in Figure 5.2. Although plots 1 and 2 were situated near the spots where the Kamphorst infiltrometer was used, comparison of the results obtained with the infiltrometer and the field rainfall simulator shows a higher infiltration rate when the infiltrometer was used (Figure 5.2). Because only a small surface area is used in the infiltrometer experiments, disturbing the sealed surface during installation of the infiltrometer device has a large impact on the infiltration rate. In case of the field rainfall simulations only the borders of the delineated experimental area are disturbed during the experimental set-up. Therefore, infiltration characteristics determined by the field rainfall simulations will correspond better to reality and are used in calculating the water harvested on the impluvium.

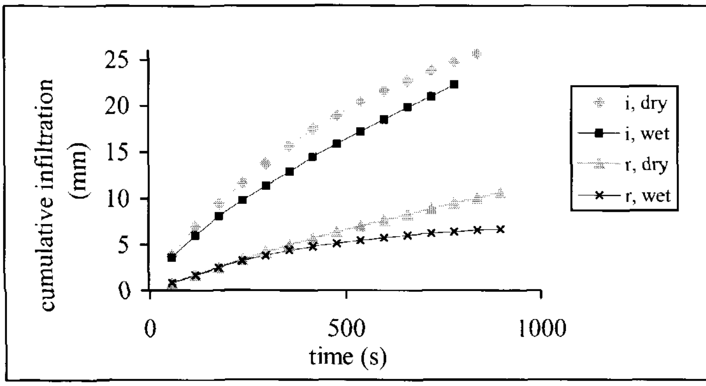

Figure 5.2 *Comparison of infiltration characteristics based on measurements with the Kamphorst infiltrometer (i) and field rainfall simulator (r) on initially dry and wet soil*

5.3.2 Sediment transport

In Figure 5.3 the unit sediment load is plotted as a function of the stream power of runoff water. The following sediment transport equation was fitted to all the measurements of the field rainfall simulations:

$$q_s = 0.00001\omega^{1.231} \qquad (R^2 = 0.846) \qquad \text{(equation 1)}$$

where:

q_s = unit sediment load (g cm^{-1} s^{-1})
ω = stream power of runoff (g s^{-3})

$$\omega = \rho\, g\, s\, q$$

where:

ρ = density of water (g cm^{-3})
g = gravitational constant (cm s^{-2})
s = slope gradient (m m^{-1})
q = unit discharge of runoff (cm^3 cm^{-1} s^{-1})

Equation 1 can be used as a general equation to estimate sediment transport in the Amrich sub-catchment. Figure 5.3 shows that Equation 1 is different from the sediment transport equations developed by Nearing *et al.* (1997) and Biesemans (2000). The equation of Biesemans predicts higher sediment load values, because this equation was derived from rainfall simulations on loose soil aggregates without stone cover. On the other hand the equation of Nearing underestimates the measurement results for low stream power values. Nearing *et al.* (1997) used flume experiments on loose soil aggregates without stone cover and rainfall impact. At low stream power values, rainfall impact seems to be important, while at higher values the increase in water level reduces the raindrop impact. The measurement results at high stream power values are overestimated by the equation of Nearing. These measurements were done on a gully causing more concentrated overland flow, and therefore having another sediment transport capacity than the rills that were investigated in the experiments of Nearing *et al.* (1997).

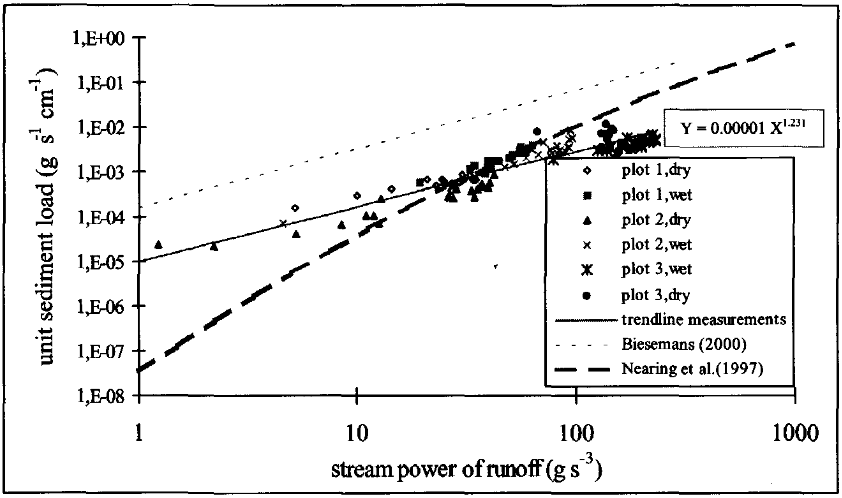

Figure 5.3 *Unit sediment load as a function of stream power of runoff for the field rainfall simulations, compared to the transport functions of Nearing et al. (1997) and Biesemans (2000)*

5.3.3 Application of the Sediment Transport Model (STM)

In order to estimate runoff and erosion on the impluvium of the Amrich jessr, the Sediment Transport Model (STM) was used. The original STM (2D-version) developed by Biesemans (2000) was modified to take better into account the characteristics of the study area. Infiltration was calculated on the basis of the Time Compression Approximation (Ibrahim and Brutsaert, 1968) using the infiltration characteristics measured during the field rainfall simulations (Figure 5.2). Overland flow was estimated by using a finite difference scheme of the kinematic wave approximation. The amount of sediment transported by runoff was assessed on the basis of Equation 1.

The modified STM (2D-version) was applied at the Amrich sub-catchment, using data of some rainfall events recorded at the gauging stations of Chouamek and El Bhayra. The area of the impluvium and terrace are 8 ha and 0.275 ha respectively. Following a detailed topographic survey of the study site, a digital elevation model (DEM) was built with a resolution of 5×5 m. Based on the DEM a slope map was calculated. The slope values were classified into 7 classes (hillslope segments). The total area of each segment and its distance from the watershed outlet were calculated. Based on these values the width of each segment was estimated (Figure 5.4) (Table 5.3).

Rainfall data of Chouamek and El Bhayra were used as input data for the modified STM. It was assumed that the soil was initially dry (soil moisture content = 0.09 g g^{-1}) before the rainfall events. The results of the simulations are given in Table 5.4. These results indicate that it is important to know the rainfall intensity during the event. High daily rainfall amounts might not cause large runoff amounts, if the rainfall intensities are low. Therefore, it is impossible to assess the probability of occurrence of a certain runoff amount on the basis of daily rainfall data.

The simulation results show that WHT like the jessr are important for erosion and flood control. Large amounts of sediment and water are collected on the terrace. The decrease in velocity of the runoff water causes deposition of sediment on the terrace. Because of the stability of the dike, the height of the spillway is limited. Therefore, only a certain part of the sediment and water can be retained on the terrace. Increasing the height of the dike may result in instability problems, causing a breakdown of the dike during high rainfall intensities. This can result in destruction of dikes of jessr systems situated downslope. The optimal height of the dike should be related to the amount of water needed for crop growth. If possible, another terrace can be constructed downslope in order to collect the remaining part of the harvested water and sediment. In case of the Amrich jessr no other terrace is actually present downslope.

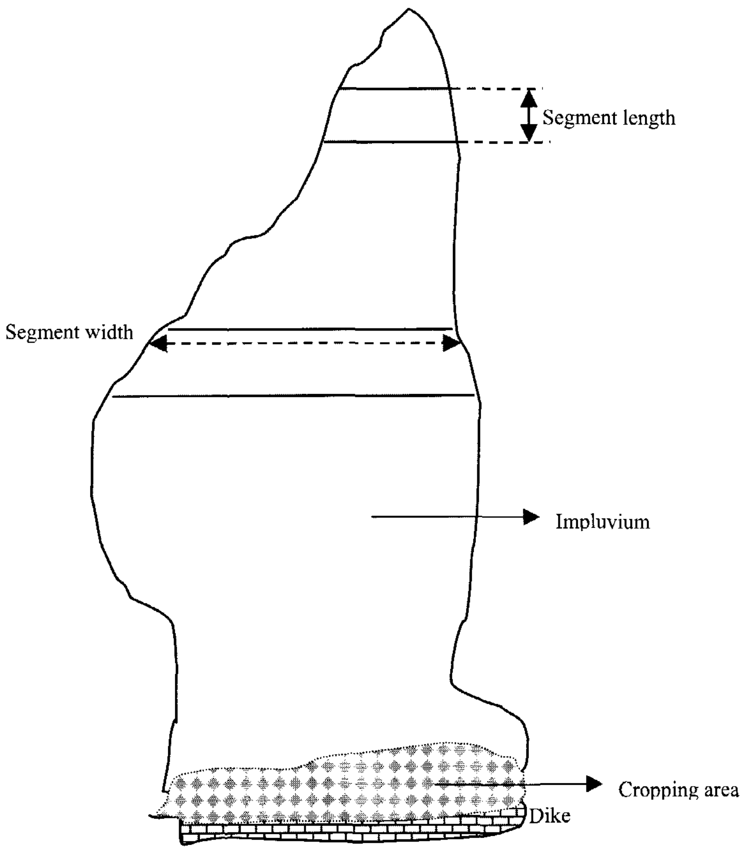

Figure 5.4 *Schematic representation of the Amrich sub-catchment*

Table 5.3 *Topographic characteristics of the Amrich sub-catchment*

Segment	*Cumulative distance to the outlet (m)*	*Altitude (m)*	*Segment width (m)*
1	0 – 77	431 – 410	207
2	77 – 120	410 – 390	249
3	120 – 162	390 – 370	269
4	162 – 207	370 – 350	284
5	207 – 293	350 – 330	254
6	293 – 349	330 – 317	94
7	349 – 374	317 – 315	100

Table 5.4 *Simulation results of the modified Sediment Transport Model (2D-version) at the Amrich sub-catchment assuming an initial dry soil (moisture content = 0.09 g g^{-1})*

Date	*Total rainfall (mm)*	*Average rainfall intensity (mm h^{-1})*	*Harvested water (m^3)*	*Harvested sediment (kg)*
21/10/1998	77.3	77	4315	50444
26/11/1999	40.0	1.8	0	0
27/04/1998	25.5	6.4	55	92
21/10/1998	24.9	60	1076	10216
25/05/2000	12.5	2.3	5	2
24/09/1998	10.4	14.5	100	378

5.3.4 Water balance

The water balance is given by the following general equation:

$$\Delta S = P + I - ET - D - R - S_o + S_i$$

where:

ΔS = change of water storage in the soil (mm)
P = rainfall (mm)
I = irrigation (mm) (i.e. harvested water from the impluvium)
ET = evapotranspiration (mm)
D = deep drainage (mm)
R = runoff (mm)
S_o = water output by subsurface flow (mm)
S_i = water input by subsurface flow (mm)

Based on the rainfall data of Chouamek (period September 1998- August 2001) (Figure 5.5) the water balance was calculated for the terrace at Amrich. Because of the shallow soil depth and the dry climatic conditions, subsurface flow was considered as being negligible. It was also assumed that runoff and deep drainage are equal to 0 and that the maximum amount of water on the terrace (by rainfall and by runoff from the impluvium) was 200 mm because of the height of the spillway. Three different scenarios were calculated:

- scenario 1: no runoff from the impluvium (i.e. irrigation I = 0)
- scenario 2: calculation of runoff from the impluvium based on the infiltration characteristic measured by the field rainfall simulator on an initially dry soil (Figure 5.2)
- scenario 3: calculation of runoff from the impluvium based on the infiltration characteristic measured by the field rainfall simulator on an initially wet soil (Figure 5.2).

These scenarios were calculated for 3 consecutive hydrologic years:

- hydrologic year 1999 (September 1998 – August 1999): wet year (annual rainfall = 325.7 mm)
- hydrologic year 2000 (September 1999 – August 2000): dry year (annual rainfall = 146.5 mm)
- hydrologic year 2001 (September 2000 – August 2001): extremely dry year (annual rainfall = 11.5 mm)

The results show that during a wet year (September 1998 – August 1999) the effect of the jessr system (i.e. the impluvium) is small (Figure 5.6, 5.7 and 5.8). Without taking into account the harvested water, optimal growing conditions occur during half of the year. In case of a dry year (September 1999 – August 2000) the runoff from the impluvium provides enough water for optimal growing conditions during at least half of the year, while without water harvesting, maximum evapotranspiration is almost never attained. During extreme dry years (September 2000 – August 2001), taking into account the amount of harvested water, maximum evapotranspiration is only attained during short time periods.

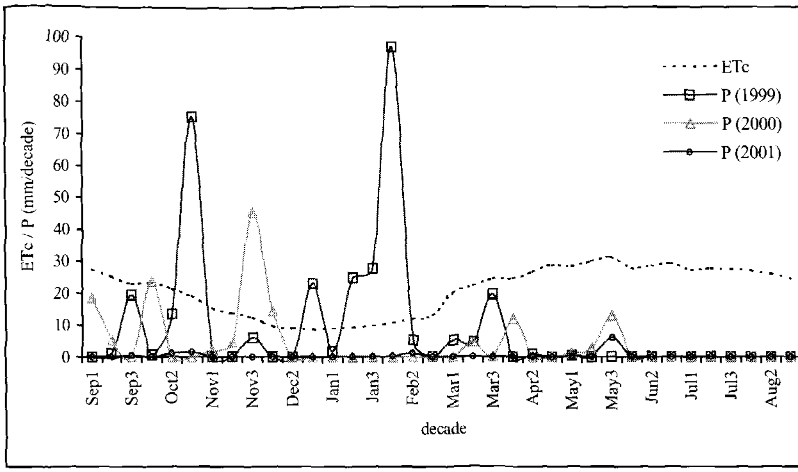

Figure 5.5 *Maximum crop evapotranspiration (ETc) (based on climatic data of Médenine (1985-1995)) and total rainfall (P) (recorded at Chouamek (September 1998 – August 2001)) per decade of days*

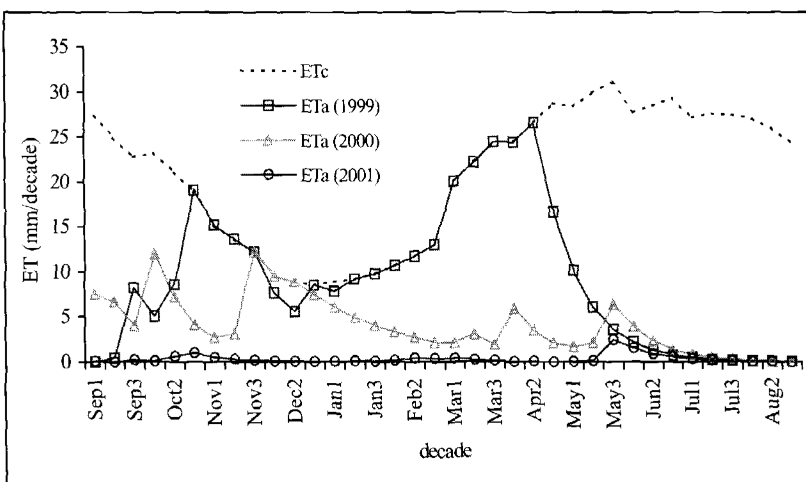

Figure 5.6 *Maximum crop evapotranspiration (ETc) and actual evapotranspiration (ETa) per decade over the period September 1998 – August 2001 (scenario 1: no irrigation)*

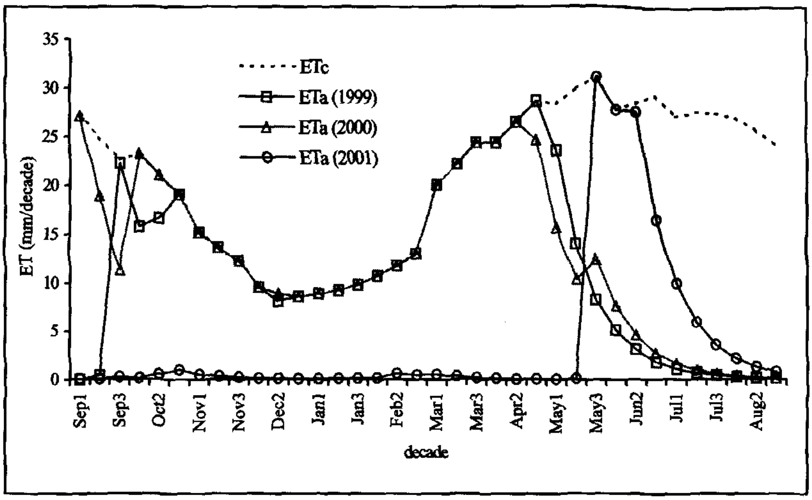

Figure 5.7 *Maximum crop evapotranspiration (ETc) and actual evapotranspiration (ETa) per decade over the period September 1998 – August 2001 (scenario 2: amount of irrigation water calculated on the basis of an initially dry soil)*

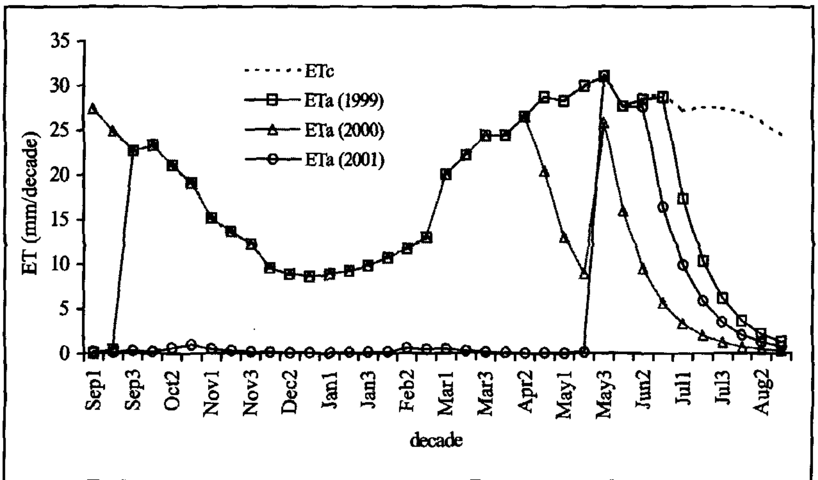

Figure 5.8 *Maximum crop evapotranspiration (ETc) and actual evapotranspiration (ETa) per decade over the period September 1998 – August 2001 (scenario 3: amount of irrigation water calculated on the basis of an initially wet soil)*

5.3.5 Catchment to cropping ratio

In the long term, a jessr can only be effective for crop cultivation if the area of the catchment (impluvium) is large enough to provide sufficient water to the crops. On the other hand, the cropping area (terrace) should be as large as possible. According to Meinzinger (2001) the minimum ratio 'impluvium/terrace' can be calculated using the equation:

$$CCR = (WR-P)/(C*P)$$

where:

CCR	= catchment to cropping ratio
	= area impluvium/area terrace (-)
P	= average annual precipitation (mm)
C	= average annual runoff coefficient (-)
WR	= annual amount of water needed by the crop (mm)

Meinzinger (2001) estimated that for olive trees the required amount of water is 500 mm y^{-1}. The average annual rainfall amount (at Béni Khedache) is 235 mm. For the period April 1998 to August 2001 the rainfall data of the weather station at Chouamek were analysed according to the Time Compression Approximation (Ibrahim and Brutsaert, 1968), using the infiltration characteristics measured during the field rainfall simulations at the site of Amrich (Figure 5.2). The runoff amounts calculated for these rainfall events gave average runoff coefficients of 0.153 and 0.217 when the infiltration characteristic of an initially dry, respectively initially wet soil was used. The median runoff coefficients were 0.064, respectively 0.147.

Using an average runoff coefficient of 0.153 and 0.217, the CCR value is 7.4, respectively 5.2. The actual CCR at Amrich is 29 (impluvium = 8 ha; terrace = 0.275 ha). Based on the CCR value of 29 and the runoff coefficient of 0.153, the minimum amount of annual rain should be 92 mm. Analysis of the rainfall data of Béni Khedache showed that, during the period 1969 – 2000, the annual rainfall amount of 92 mm is exceeded in 97 % of the years.

Additionally to the CCR value also other factors have to be taken into account to obtain sufficient water supply for crop production, e.g. the number of olive trees should be not too large, otherwise competition for water will decrease the yield. Also the spillway should be high enough in order to retain enough water on the terrace to increase the soil water content to field capacity till the rooting depth of the crop.

5.4 Conclusions

In this study the effect of a jessr in the Oued Oum Zessar watershed was examined on soil and water conservation. Rainfall simulations provided input data about infiltration and sediment transport, which were used to simulate runoff and erosion during rainfall events. These simulation results indicated that large amounts of runoff and sediment are collected on the terrace. Therefore, the jessr plays an important role in reducing transport of water and sediment downslope. Over a period of 3 consecutive years the water balance of the terrace was assessed. This showed that especially during dry years the impluvium provides an important additional amount of water needed for the cultivation of olive trees on the terrace. Furthermore, it was found that the 'catchment to cropping ratio' (CCR) should be larger than 7.4 in order to provide, on average, a sufficient amount of water for the cultivation of olive trees. However, other factors like the number of olive trees and the height of the spillway also have to be taken into account.

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6 THE ROLE OF SEGUIAS IN SOIL AND WATER CONSERVATION WITHIN THE TALKJOUNTE WATERSHED

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Abstract

In the arid regions of Morocco, water harvesting techniques (WHT) like seguias are commonly applied. The seguia system directs water from a main river (wady) towards small, delineated parcels that are used for cropping. This additional water supply allows crop production even in arid climatic conditions. However, seguias also play an important role in soil and water conservation (SWC). Although rainfall is limited in arid regions, rainfall intensities can be very high causing severe erosion and runoff. Together with runoff water also sediment is directed to the seguias. This increases the soil depth and hence the water storage capacity within the seguia area, but also decreases the amount of sediment deposition downstream and consequently the off-site impact of erosion.

In this study, the revised Morgan-Morgan-Finney model (rMMF) is used to assess monthly and annual runoff and soil losses in the Talkjounte watershed, situated in the Western High-Atlas Mountains in Morocco. At Imi El Kheng, at the outlet of this watershed, a dam has been built in 1993, with the objective of providing water for irrigated agriculture in the downstream Souss Valley. Comparison of the simulation results with the measured sediment deposition in the reservoir behind the dam of Imi El Kheng indicates that the rMMF model might be useful in the assessment of runoff and soil losses within the Talkjounte watershed. However, more accurate input data are needed in order to validate this model properly.

In order to assess the impact of seguias on the water availability and the off-site effects of erosion, a comparison is made between natural and actual landuse. The simulation results of the rMMF model indicate that the seguias have an important impact on SWC in the Talkjounte watershed. Under the actual landuse (with seguias) the average annual runoff and sediment output are reduced by 44 respectively 45 %, compared to the natural landuse (without seguias). This is mainly due to the deviation of water and sediment from the wady to the seguias. This stresses that seguias form an important factor in controlling the silting up of the reservoir. It is argued that with present strategies for water resources management in the area and limited possibilities for economic development for the upstream rural population, trends of outmigration will ultimately lead to a declined interest in maintaining the seguias, with important implications for the economic life of the reservoir.

Keywords: Seguia, Morocco, erosion, runoff, water harvesting, sedimentation

6.1 Introduction

Water harvesting techniques (WHT) like seguias are commonly applied in Morocco. A seguia is a man-made hydrological system consisting of irrigation channels that divert water from a main river (wady) towards small, delineated parcels that are used for cropping. By this additional water supply crop production becomes possible even in arid climatic conditions. However, seguias also play an important role in soil and water conservation (SWC). Although rainfall is limited in arid regions, rainfall intensities can be very high, causing severe erosion and runoff. Together with runoff water also sediment is directed to the seguias. This increases the soil depth and hence the water storage capacity within the seguia area, but also decreases the amount of sediment deposition downstream and consequently the off-site impact of erosion.

In this study, an empirical model is used to assess monthly and annual runoff and soil losses in the Talkjounte watershed, situated in the Western High-Atlas Mountains in Morocco. Moreover, simulations are done to examine the impact of seguias on the water availability and the off-site effects of erosion, notably the silting up of the reservoir behind the dam of Imi El Kheng, built in 1993.

6.2 Materials and methods

6.2.1 Study area

The Talkjounte watershed with an area of 289 km² was selected to assess the impact of seguias on overland flow and erosion. The elevation of the Talkjounte watershed varies from 575 m in the south to 3035 m in the north (Figure 6.3). The Talkjounte watershed is situated north-east of the town of Taroudannt. Its central point is the village Ida Oublal, located at 30°46' N, 8°34' E. The watershed is bordered by the Tichka massif in the north, the mountain ranges Tazgoukht and Tamdaka in the west, the villages Abzouiane and Tilekent in the east and the dam Imi El Kheng in the south, constructed at the outlet of the watershed.

6.2.2 The revised Morgan-Morgan-Finney model

The revised Morgan-Morgan-Finney model (rMMF model) (Morgan, 2001) was used to assess annual overland flow and soil loss within the Talkjounte watershed. The original Morgan-Morgan-Finney (MMF) model (Morgan *et al.*, 1984) has been used successfully in a wide range of environments ranging from Indonesia (Besler, 1987) to the Rocky Mountains (Morgan, 1985). The model has been used by De Jong (1994) to develop SEMMED (Soil Erosion Model for Mediterranean areas). Morgan (2001) stated that the rMMF-model describes better the erosion processes compared to the original MMF model and provides more input data for different environmental conditions.

Van de Voort (2001) applied the original MMF model in the Talkjounte watershed, but the results underestimated the sediment yield measured in the lake at the outlet of the watershed. Therefore, it was decided to use the revised MMF model, because some equations take into account more (interactive) subprocesses. On the other hand more values are given for different input parameters, which is useful if input data are limited or are difficult to assess.

The rMMF model was slightly adapted and incorporated in a Geographical Information System (GIS) in order to determine overland flow direction and cumulative runoff and soil loss. The model separates the erosion process into 2 phases: a water phase and a sediment phase. The water phase determines the runoff volume and the energy of the rainfall available to detach soil particles. In the sediment phase rates of soil particle detachment by rainfall and runoff are determined along with the transport capacity of runoff. Total particle detachment and transport capacity are compared and the erosion rate is equated to the lower of the two rates. The outcome of the model gives an annual soil loss, caused by detachment of soil particles by raindrop impact (detachment limited condition) or transport of these particles by overland flow (transport limited condition). A more detailed description of the model is given by Morgan (2001).

6.2.3 *Input data of the rMMF model*

The input data concerning topography, soil, landuse and rainfall were obtained by field surveys (Van de Voort, 2001). Additional data required by the rMMF model were collected from tables published by Morgan (2001). All the input data were converted into raster maps (pixel resolution: 50 m) in a GIS. Two different scenarios were compared in order to assess the impact of the seguias on overland flow and soil loss: natural landuse (without seguias) and actual landuse (with seguias). Under natural landuse the cultivation of cereals is replaced by argane forest, and the seguias by cereals (Figure 6.1). The natural landuse scenario could be expected when outmigration of the population continues and primary economic activities within the catchment areas are discontinued due to labour shortage. This trend will first affect the most labour-intensive components of the landuse system, i.e. the seguias and cereal production. Under natural landuse only orchards are cultivated on terraces, while under the actual landuse orchards and seguias have a terrace system.

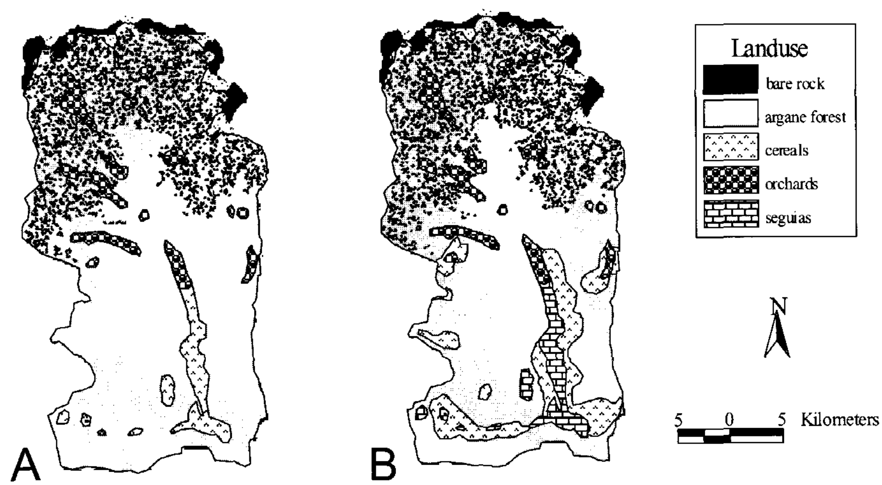

Figure 6.1 *Natural (A) and actual (B) landuse in the Talkjounte watershed*

Precipitation data were only available to a limited extent: monthly rainfall data were recorded over the period 1994-2000 at the Imi weather station in the Talkjounte watershed. The average annual precipitation at the weather station of Imi over the period September 1994 – August 2000 was 336.8 mm, with most rainfall occurring in the period from December till March. However, annual rainfall varied within a range of 117.9 – 744.8 mm (coefficient of variance = 64%). The annual number of rain days (55) in the watershed was assessed on the basis of a short-term database available at www.weeronline.com, where data were used from the weather station of Marrakech over a period of 5 years. The weather station of Marrakech was chosen because of its close distance to the Talkjounte watershed, and because it is situated in a similar inland mountain area environment at a height of 466 m. Average monthly rainfall and number of rain days are given in Figure 6.2. The intensity of erosive rain was set equal to 30 mm h^{-1}, according to the data given by Morgan (2001) for Mediterranean zones. On the basis of the rainfall intensity value of 30 mm h^{-1} the kinetic energy was calculated according to the equation proposed by Coutinho and Tomas (1995), resulting in a kinetic energy value KE equal to 28.65 J m^{-2} mm^{-1}.

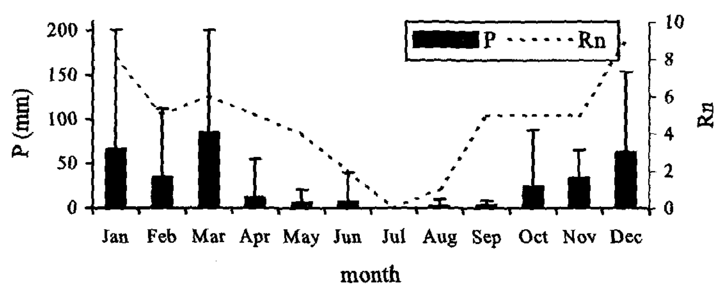

Figure 6.2 *Average monthly rainfall P (period 1994-2000) recorded at the Imi weather station (error bars indicate maximum and minimum rainfall values) and number of rain days Rn recorded at the weather station of Marrakech*

Land use has been mapped based on field observations. Land use in the Talkjounte watershed can be subdivided in three parts from high to low elevation respectively: rock outcrops, argane forest and agricultural land use (Figure 6.1). The argane forest, on average, consists of 18 trees per hectare. It is present on all hillsides except for the mountains bordering the northern part of the watershed. Land use in the seguias from Ida Oublal until the reservoir of the dam is fairly homogeneous. It consists of a mixed cropping pattern of trees (e.g. olive, almond and date palm) and crops (e.g. barley, clover and beans).

The effective hydrological depth (EHD) of soil was set equal to 0.05 m for the argane forest, because this land use type is situated on shallow, crusted soils on steep slopes. For bare rock an EHD value of 0 was used, while for the remaining land use types the EHD value was set equal to 0.12. To the EHD value 0.01 was added for terraces. The C-value was multiplied by 0.15 for terraces. The other input data of the rMMF model related to land use are given in Table 6.1.

Table 6.1 *Land use input data for the rMMF model based on field observations and guide values given by Morgan (2001)*

Land use	*A*	*Et/Eo*	*C*	*CC*	*GC*	*PH*
Rock	0	0.05	1	1	1	0
Argane	0.1	0.3	0.35	0.15	0.05	1.5
Cereals	0.25	0.6	0.2	0.6	0.6	0.25
Orchards	0.2	0.4	0.053	0.25	0.05	2
Seguia	0.3	0.6	0.015	0.6	0.6	2

A = proportion of the rainfall intercepted by the vegetation or crop cover
Et/Eo = ratio of actual (Et) to potential evapotranspiration (Eo)
C = crop cover management factor (combination of C and P factors of the Universal Soil Loss Equation)
CC = canopy cover (m^2 m^{-2})
GC = ground cover (m^2 m^{-2})
PH = plant height (m)

In the Talkjounte watershed 36 soil samples were taken in different landuse types. Soil texture was determined on these 36 samples by sieving and slime Analysis (Van de Voort, 2001). However, these measurements were insufficient to map the whole watershed. Therefore, the 36 samples were classified according to Soil Taxonomy and the percentage of occurrence of the different soil textures within every landuse type was calculated. Afterwards a soil texture class was assigned randomly to every pixel, taking into account the calculated percentages (Van de Voort, 2001). The most dominant soil texture classes are silt loam, sandy loam and clay loam. Based on the soil texture class of every pixel, the soil moisture content at field capacity (MS), bulk density (BD), soil detachability (K) and cohesion of the surface soil (COH) were estimated, taking into account field observations and guide values given by Morgan (2001) (Table 6.2).

Based on field observations as well as the soil map of the Talkjounte watershed (Université Ibn Zohr, 1999), soils on crystalline rock were considered as being little evolved. These 'soils' are present above 2500 m. Between 1560 m and 2500 m 10% of the argane forest was indicated as bare rock using a random distribution. The border of 1560 m was used because above this altitude no crops are cultivated.

Table 6.2 *Soil input data based on field measurements and guide values given by Morgan (2001) and Morgan et al. (1982)*

Soil type	*MS*	*BD*	*K*	*COH*
Rock	0	2.64	0	100
Sand	0.08	1.5	1.2	2
Fine sand	0.15	1.4	0.5	2
Sandy loam	0.28	1.2	0.7	2
Silt loam	0.25	1.3	0.9	3
Clay loam	0.40	1.3	0.7	10

MS = soil moisture content at field capacity ($g\ g^{-1}$)
BD = bulk density of the top soil ($Mg\ m^{-3}$)
K = soil detachability index ($g\ J^{-1}$)
COH= cohesion of the surface soil as measured with a torvane under saturated conditions (kPa)

6.3 Results and discussion

6.3.1 Runoff losses estimated by the rMMF model

Using the rMMF-model the average annual amount of overland flow was calculated under natural and actual conditions over a 6-year period (September 1994 – August 2000). Taking into account the actual landuse it was assumed that no water or sediment leaves the seguia area, because of the terrace system and the dikes surrounding the seguias. No detailed data are available about the number and location of the points where water is deviated from the wady to the seguias. Also the fraction of the water in the wady that is directed towards the seguias is unknown. In this study it was assumed that water only enters the seguias at 10 irrigation points (Figure 6.3). At these irrigation points 10% of the water in the wady is drained away towards the seguias.

Table 6.3 and 6.4 give the calculated annual amount of infiltration and irrigation water per landuse type under natural conditions, respectively actual conditions. The highest infiltration values are found for orchards, cereals and seguias because of the high EHD and terrace system. The average amount of water leaving the watershed (entering the reservoir) is 4.63 10^7 m^3 y^{-1} under the natural conditions and 2.60 10^7 m^3 y^{-1} under the actual conditions: about 44% more water is retained inside the watershed by the seguias. The decrease in total water output under the actual landuse is caused by the larger area used for crop production (providing more infiltration and rainfall interception by cover than the argane forest) and the deviation of a large part of the runoff from the wady to the seguias.

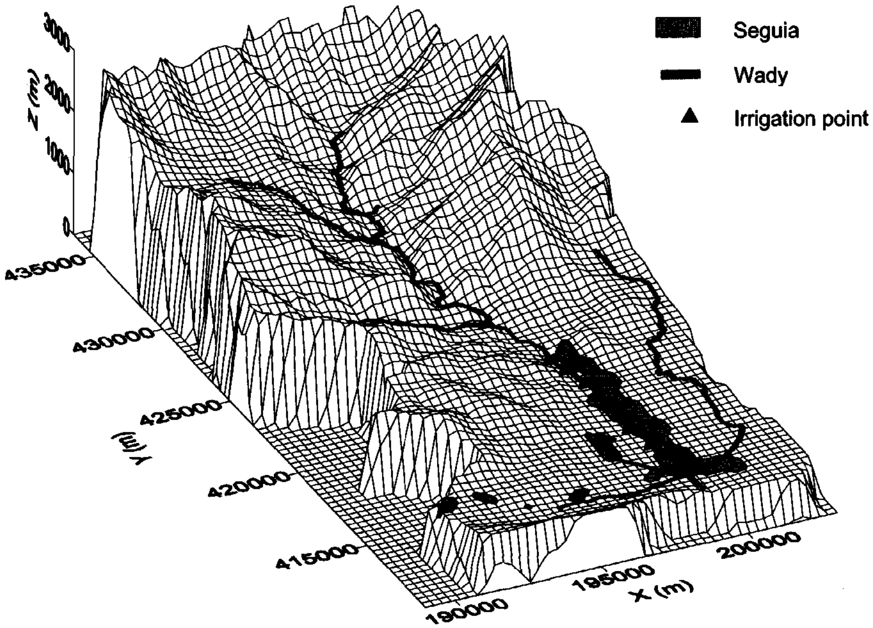

Figure 6.3 *Digital elevation model of the Talkjounte watershed with indication of the wady, seguias and irrigation points*

Table 6.3 *Average annual amount of infiltration per landuse type calculated by the rMMF model taking into account the natural landuse (average total rainfall = 336.8 mm)*

Landuse type	*Area* (10^6 m^2)	*Infiltration (mm)*
bare rock	23.39	0
Argane forest	214.55	179.2
Argane forest [1]	26.22	187.6
Orchards	14.30	293.5
Cereals	10.92	330.6

Note 1: This part of the argane forest is used for cereals under actual landuse (Table 6.4)

Table 6.4 *Average annual amount of infiltration and irrigation water per landuse type calculated by the rMMF model taking into account the actual landuse (average annual rainfall = 336.8 mm)*

Landuse type	*Area* (10^6 m^2)	*Infiltration (mm)*	*Irrigation (mm)*
Bare rock	23.39	0	0
Argane forest	214.55	179.2	0
Cereals	26.22	330.0	0
Orchards	14.30	293.5	0
Seguia	10.92	336.8	1519.8

Table 6.5 gives the simulation results of the rMMF model in case the average, minimum and maximum annual precipitation over the period 1994-2000 are used as input, keeping the other input data unchanged. The runoff output does not vary proportionally with the rainfall amounts, but as concerns the actual landuse a similar proportional reduction in runoff output can be observed for the different rainfall amounts. In all cases the reduction is mainly caused by the deviation of water towards the seguias.

Table 6.5 *Simulated annual runoff output (R_{output}) of the Talkjounte watershed and runoff input (R_{input}) in the seguias for the average, maximum and minimum annual precipitation amount over the period September 1994-August 2000*

Precipitation (mm)	*Natural landuse*	*Actual landuse*	
	R_{output} (10^6 m^3)	*R_{output} (10^6 m^3)*	*R_{input} seguias (10^6 m^3)*
336.8	46.3	26.0	16.6
744.8	149.0	85.6	52.1
117.9	6.4	3.5	2.7

6.3.2 Soil losses estimated by the rMMF model

Besides the calculation of the overland flow, also the amount of erosion was assessed using the rMMF model. Taking into account the actual landuse, it was assumed that no sediment leaves the seguia area and that sediment only enters the seguias by the 10 selected irrigation points. At these irrigation points 10% of the sediment transported in the wady is directed towards the seguias. Table 6.6 and 6.7 give the calculated annual amount of sediment loss per landuse type. Most erosion occurs where argane forest is present, because in that case only little cover protects the soil. The average sediment output entering the reservoir at the watershed outlet is 2.18 10^8 kg y^{-1} under the natural conditions and 1.20 10^8 kg y^{-1} under the actual conditions. This is a reduction of the average annual sediment output by 45 %, mainly caused by the deviation of water and sediment from the wady to the seguias.

Table 6.6 *Average annual amount of sediment loss per landuse type calculated by the rMMF model taking into account the natural landuse*

Landuse type	*Area (10^6 m^2)*	*Sediment loss (kg m^{-2} y^{-1})*
Bare rock	23.39	0.000
Argane forest	214.55	0.940
Argane forest [1]	26.22	0.464
Orchards	143.03	0.031
Cereals	10.92	0.000

Note 1: This part of the argane forest is used for cereals under actual landuse (Table 6.7)

Table 6.7 *Average annual amount of sediment loss and deposition per landuse type calculated by the rMMF model taking into account the actual landuse*

Landuse type	*Area (10^6 m^2)*	*Sediment loss (kg m^{-2} $^{-1}$)*	*Sediment deposition (kg m^{-2} y^{-1})*
Bare rock	23.39	0.000	0.00
Argane forest	214.55	0.940	0.00
Cereals	26.22	0.001	0.00
Orchards	14.30	0.031	0.00
Seguia	10.92	0.000	7.89

The last estimation of the amount of sediment collected in the reservoir behind the dam of Imi El Kheng was made in March 2000 when 35 bathymetric profiles with equidistances of 50 m were measured in the deposited sediment of the reservoir. It was estimated that the average sediment input into the reservoir is equal to 101600 m^3 y^{-1}. Taking into account an average bulk density of sediment equal to 1100 kg m^{-2}, it means that every year 1.12 10^8 kg of sediment is deposited in the reservoir at the watershed outlet. This value is in good agreement with the value of 1.20 10^8 kg y^{-1} that was estimated for the actual landuse conditions. It can be concluded that the rMMF model gives promising results, but more accurate input data are needed in order to validate this model properly.

Table 6.8 gives the simulation results of the rMMF model in case the average, minimum and maximum annual precipitation over the period 1994-2000 are used as input, keeping the other input data unchanged. The sediment output does not vary proportionally with the rainfall amounts, but comparing the natural and actual landuse shows a similar proportional reduction in sediment output for the different rainfall amounts. In all cases the reduction is mainly caused by the deviation of water and sediment towards the seguias.

Table 6.8 *Simulated annual sediment output (S_{output}) of the Talkjounte watershed and sediment input (S_{input}) in the seguias for the average, maximum and minimum annual precipitation amount over the period September 1994-August 2000*

Precipitation	*Natural landuse*	*Actual landuse*	
(mm)	S_{output} *(10^6 kg)*	S_{output} *(10^6 kg)*	S_{input} *seguias (10^6 kg)*
336.8	218	120	86.2
744.8	880	487	345
117.9	7.35	4.02	3.23

With a volume of the reservoir of 11 Mm^3, it can be concluded that silting up rates are increased from 1.0% to 1.8% per year when actual landuse is replaced by natural landuse. Accordingly, the time to complete fill-up of the reservoir with sediments would be reduced from 101 to 56 years. Reduction of the economic life of the reservoir would proceed even faster because relative evapotranspiration losses will gradually increase.

6.3.3 Assessment of the monthly water input in the seguias

Although the rMMF model is primarily developed to estimate annual soil and water losses, it is also used in this study to assess the monthly water losses in the Talkjounte watershed, in order to examine how the water input in the seguias is distributed over time. Average monthly rainfall data (period September 1994-August 2000) and number of rain days in each month (Figure 6.2) were used as input in the rMMF model. The simulation results indicate that the runoff input into the seguias is unequally distributed over a year (Figure 6.4). Although the total annual runoff input into the seguias is 1519.8 mm, the water supply by the wady is very limited during half of the year (April – September). During the other part of the year, it is possible that too much water enters the seguias. In that case it is a common practice that the surplus of water is directed again towards the wady. Most of the sediment however will be retained within the seguias because of deposition caused by a decrease in flow velocity.

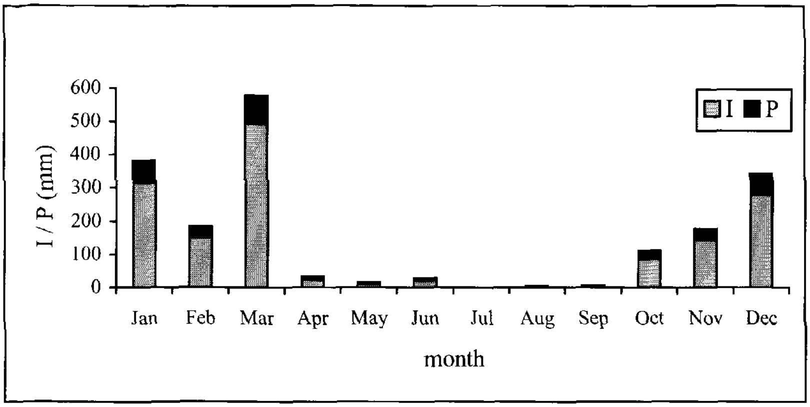

Figure 6.4. *Monthly rainfall (P) and runoff input (I) into the seguias of the Talkjounte watershed*

6.4 Conclusions

In this study the rMMF model was used to estimate the runoff and soil losses within the Talkjounte watershed. Comparison of the simulation results with the measured sediment deposition in the reservoir behind the dam of Imi El Kheng indicates that the rMMF model might be useful in the assessment of runoff and soil losses within the Talkjounte watershed. However, more accurate input data are needed in order to validate this model properly.

Based on the simulation results of the rMMF model, it can be seen that the seguias have an important impact on soil and water conservation in the Talkjounte watershed. Under the actual landuse (with seguias) in the Talkjounte watershed the average annual runoff and sediment output are reduced by 44 respectively 45 %, compared to the natural landuse (without seguias). This is mainly due to the deviation of water and sediment from the wady to the seguias. These results show that seguias perform an important role in diminishing the velocity of silting up of the reservoir and hence prevent a reduction of its economic life. This stresses that efforts should be taken to counter trends of out-migration and reduced interest in maintaining seguias.

Acknowledgements

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7 IMPACT DES TRAVAUX DE CONSERVATION DES EAUX ET DES SOLS SUR LA RECHARGE DE LA NAPPE DE ZEUSS- KOUTINE

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Abstract

The Zeuss-Koutine aquifer represents the main water reservoir for water supply (drinking, tourism, irrigation, industry, etc.) of the two provinces Médenine and Tataouine of south-eastern Tunisia. It is a multi aquifer system spreading over an area evaluated at 785 km² with a mean annual rainfall of 190 mm. Its potential resources are estimated to 350 l s^{-1}.

The exploitation of this reservoir has started in 1962, but effectively only in 1972. Its continuous monitoring has shown that the abstraction rate increased from 102 l s^{-1} in 1974 to 420 l s^{-1} in 1996. It resulted in a decline of the mean piezometric level (PL) of 11.3 m.

To cope with this problem an ambitious program for surface water mobilisation has been implemented since 1990 in order to ensure the replenishment of this overexploited water table. In fact, more than 300 recharge and flood spreading units have been realised on the drainage watersheds (Oueds Om Zessar, Zeuss and Oum Tamr). It resulted in the stabilisation and even amelioration of the PL since 1997. On the other hand, the pumping of this reservoir induced a vertical homogenisation of the chemical characteristics that resulted then in an increase in the salinity of the surface layers and a decrease in the salinity of the deep aquifers. However, it is expected that the 'artificial' recharge will, in the long term, be able to damp and/or stop the salinity increase phenomenon.

It is important to note that the intensification of the soil and water conservation programs does not only concern the ground water but has multiple impacts such as flooding and erosion control, extension of cultivated farms, range lands use, etc. Especially when addressing this problem at the level of the whole watershed.

The simulations of the impact of the soil and water conservation works on the groundwater aquifer by mathematical models show that the contribution of these works is very significant. The average natural infiltration in the groundwater aquifer, which was approximately 290 l s^{-1} before the construction of the conservation works, increased since 1985 to 320 l s^{-1}, so the aquifer could profit in spite of the rainfall deficit recorded during the majority of this period. That is a contribution of additional water of about 30 l s^{-1}.

Keywords: Arid, recharge, groundwater harvesting, Tunisia.

7.1 Cadre hydrologique

La nappe de Zeuss-Koutine s'étend sous les bassins versants des oueds Zigzaou, Zeuss, Sidi Makhlouf, Om Zessar et la partie centrale du bassin versant d'oued Om et-Tamar, ainsi qu'une petite étendue du bassin versant d'oued Smar. Elle couvre une superficie évaluée à 785 km².

Quatre pluviomètres assurent l'enregistrement de la pluviométrie sur les bassins versants de Zeuss-Koutine. Dans un climat méditerranéen, saharien supérieur, avec une variante sub-littorale, cette pluviométrie est très irrégulière dans l'espace et dans le temps. Le tableau 7.1 illustre les pluviométries maximales, minimales et moyennes observées au niveau des stations de Medenine, Koutine, Zeuss et Loudyette alors que le tableau 7.2 indique la pluviométrie moyenne mensuelle au niveau de la station de Medenine.

Tableau 7.1 *Pluviométries annuelles, maximales, minimales et moyennes sur les régions de Zeuss Koutine*

Pluviométrie	*Station*			
(mm an^{-1})	*Medenine SM*	*Koutine*	*Zeuss (St Pomp.)*	*Loudyette*
Maximales	472	591	262	257
Minimales	37	73	177	119
Moyennes	152	211	214	171
Nbre d'an. d'obs.	85	18	5	3

Tableau 7.2 *Pluviométries mensuelles moyennes à la station météorologique de Medenine.*

Mois	*Sep.*	*Oct.*	*Nov.*	*Déc.*	*Jan.*	*Fév.*	*Mars*	*Avr.*	*Mai*	*Juin*	*Juil.*	*Août*	*Obs.*
P (mm)	12	24	18	18	20	17	22	13	6	1	0	1	85
P (%)	8	16	12	12	13	11	15	8	4	1	0	1	

La carte des isohyètes interannuelles montre un tracé assez régulier d'orientation approximative nord-ouest sud-est qui sont parallèles à la côte de la Méditerranée et aux reliefs du Dahar. Sur la zone de Zeuss-Koutine, la pluviométrie moyenne varie de 170 mm an^{-1} à 190 mm an^{-1}.

Le coefficient de ruissellement annuel moyen a été évalué à 7 % de la pluviométrie annuelle moyenne (Fersi, 1985). Ce coefficient a été calculé à partir des données hygrométriques mesurées sur les stations de Koutine et d'oued Om Zessar observées depuis 1973/74. Toutefois, il faut noter que l'intensification des travaux de Conservation des Eaux et des Sols en amont des bassins versants contribuant à la recharge de la nappe de Zeuss-Koutine ont modifié les paramètres des écoulements au niveau de ces bassins.

7.2 Cadre hydrogéologique

7.2.1 Géométrie des réservoirs

La nappe de Zeuss-koutine est logée dans les niveaux lithostratigraphiques suivants :
a) les calcaires et les dolomies du Jurassique supérieur (Callovien-Oxfordien),
b) les calcaires dolomitiques du l'Albo-Aptien,
c) les dolomies et les calcaires dolomitiques du Turonien,
d) Les calcaires du Sénonien inférieur qui se subdivisent en deux entités distinctes :
   - L'unité calcaire intermédiaire du Sénonien marno-gypseux (horizon B),
   - L'unité calcaire sommitale (horizon A).

La corrélation lithostratigraphique et hydrogéologique à travers les sondages d'oued Zeuss (Fig 7. 2) matérialise le fonctionnement hydraulique de la nappe de Zeuss-Koutine au niveau de cette zone avec différenciation de divers niveaux aquifères susmentionnés. Il s'agit d'un système aquifère à plusieurs compartiments qui communiquent par l'intermédiaire des failles et éventuellement par drainance. Les calcaires et dolomies du Jurassique et de l'Albo-Aptien de ce système aquifère sont discordants sur les grès du Trias.

7.2.2 Recharge et exploitation

L'écoulement souterrain de la nappe de Zeuss-Koutine se fait vers le sud-est en direction de la mer Méditerranée. La carte piéozmètrique de cette nappe fait apparaître trois principaux axes d'écoulement (Gaubi, 1988) :

a) Un écoulement parallèle à l'oued Zigzaou et en provenance essentiellement des formations aquifères du Crétacé inférieur et du Jurassique de Gabès Sud,
b) Un écoulement longeant oued Bou Ramli et oued Zeuss. Cet écoulement est dû à l'alimentation à partir des grès du Trias.
c) Un écoulement longeant oued Koutine traduisant une alimentation in-situ des calcaires du Jurassique appuyé par une alimentation à partir des grès du Trias.

La carte de recharge de la nappe envisagée a été établie en se basant sur les données géologiques et hydrogéologiques et notamment celles des forages (Figure 7.1). Cette carte montre deux zones d'alimentation préférentielle qui sont :

a) Une zone d'affleurement de l'Albo-Aptien au nord-ouest de la région,
b) Une zone d'affleurement du Jurassique limitée au nord-est par la faille de Medenine, au nord-ouest par une faille passant au piémont oriental des monts de Touati et de Debâ et au sud-ouest par les grès du Trias inférieur et par le Permien.

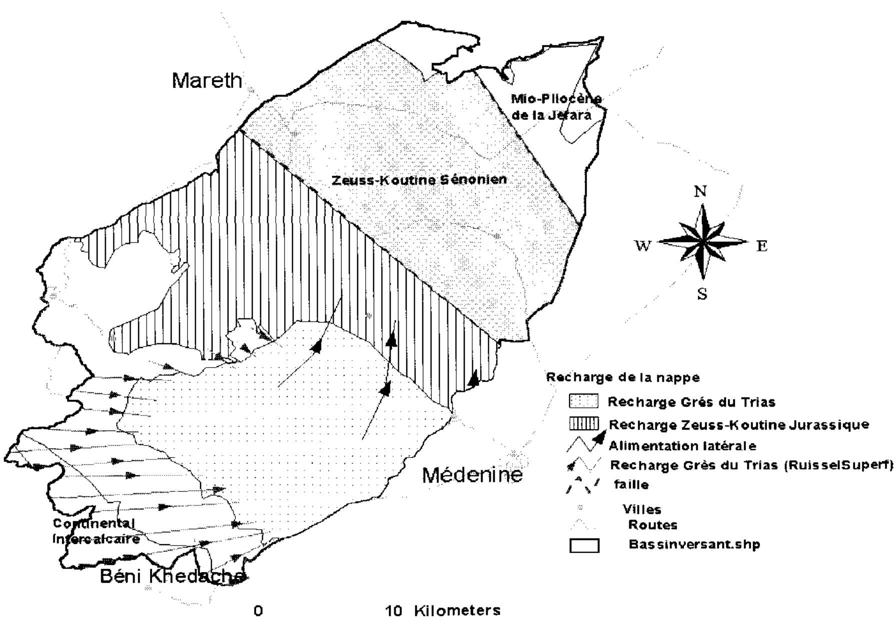

Figure 7.1 *Zones de la recharge de la nappe*

Cette nappe est exploitée depuis 1962 pour l'alimentation en eau potable des agglomérations et villes du sud-est tunisien. Les ressources renouvelables ont été estimées à 350 l s^{-1}. Le débit annuel moyen d'exploitation a dépassé cette valeur depuis 1986 (Figure 7.2). L'exploitation mensuelle est très fluctuante. Par exemple, pour un débit d'exploitation en 1996 de 420 l s^{-1} (D.G.R.E.,1996), la pointe estivale a atteint en mois d'août un débit de 556 l s^{-1} alors que celle hivernale n'est que de 278 l s^{-1}.

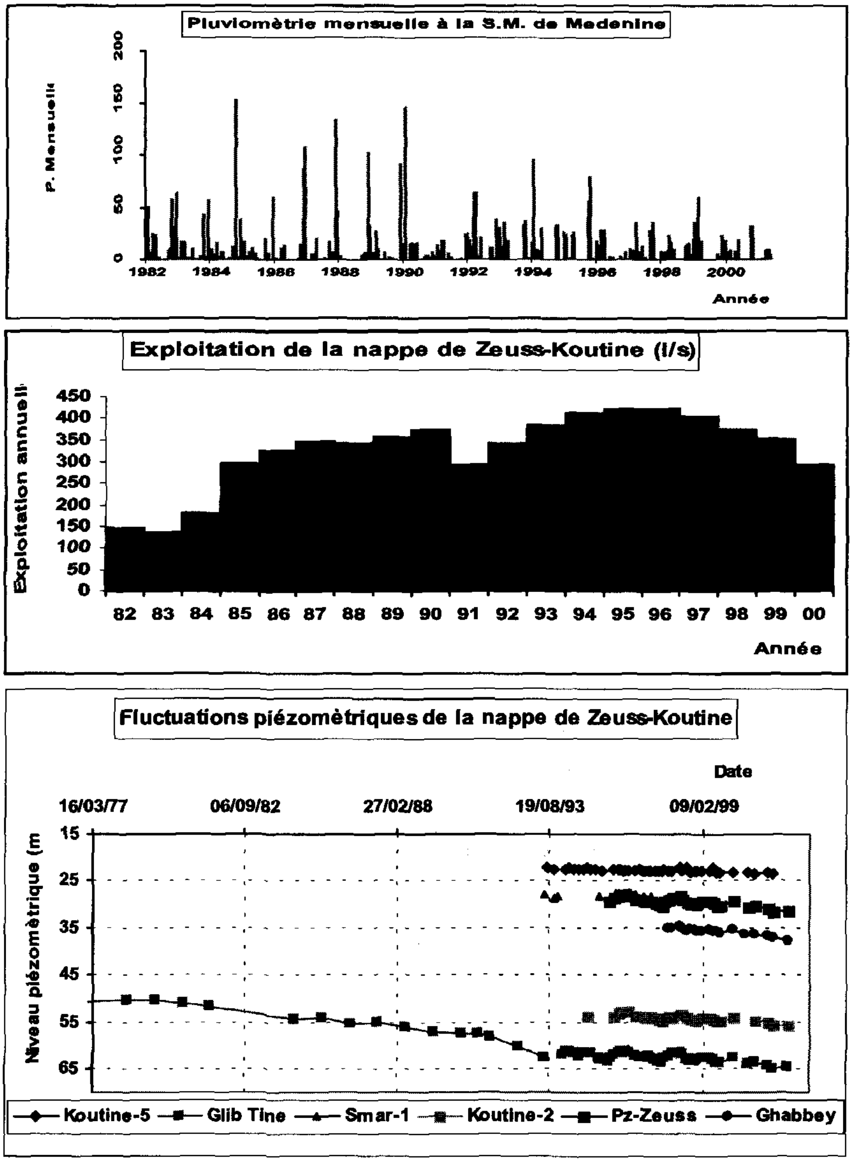

Figure 7.2 *Evolution piézomètrique du complexe carbonaté de la nappe de Zeuss-Koutine en fonction de la pluviométrie et de l'exploitation.*

7.3 Travaux de conservation des eaux et des sols (C.E.S.)

Dans cadre de la stratégie de mobilisation des eaux de surface et afin de renforcer la recharge de la nappe surexploitée de Zeuss-Koutine, plus des 300 ouvrages, contribuant à la recharge de cette nappe, ont été réalisées sur les bassins versants des oueds Om Zessar, Zeuss et Om et-Tamar.

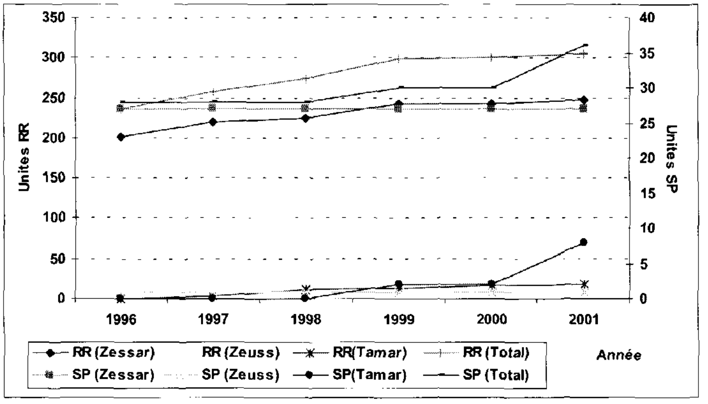

Figure 7.3 *Ouvrages de recharge de la nappe et ouvrages d'épandage des eaux des crues réalisés sur les bassins versants de Zeuss-Koutine (Situation arrêtée au 31/12/2001).*

Les sites de ces différents aménagements ont été choisis à la lumière des données hydrologiques et hydrogéologiques concernant la région de telle façon qu'ils favorisent une infiltration maximale au niveau des ouvrages réalisés (Figure 7.3).
Les aménagements anti-érosifs réalisés assureront, outre la recharge des réservoirs d'eau souterraine, la mise en valeur intégrée sur les bassins versants traités.

7.4 Impact des travaux de C.E.S. sur la recharge de la nappe

7.4.1 Ruissellement, fluctuations piézomètriques et recharge

Ruissellement
En se basant sur les données hydrométriques mesurées au niveau des stations de Koutine et d'oued Om Zessar depuis 1973 et sur les mesures de ruissellement effectuées sur les différents cours d'au de la zone, l'estimation des volumes d'eau ruisselée durant années pluvieuses sont consignés dans le tableau suivant:

Tableau 7.3 *Estimation des volumes des eaux ruisselées lors de principaux épisodes pluvieux (bassins versants de Zeuss-Koutine. Années: 1995, 1997 et 1998)*

Episode pluvieux	*P moy 'épisode (mm)*	*Volume ruisselé (10^6 m^3)*	*Observations*
Sept et oct. 1995	46 à 148	29,4	Crues dispersées et eau de ruissellement retenue en totalité par les ouvrages CES
Sept. 1997	60 à 80	15,7	Crues dispersées et eau de ruissellement retenue en totalité par les ouvrages CES
Octobre 1998	75 à 90	10,63	Crues en amont des B.V. de Zeuss-Koutine. Ecoulement d'oued Koutine jusqu'à la mer.

Fluctuations piézométriques

Les fluctuations piézométriques de la nappe de Zeuss-Koutine ont été suivies depuis 1965 par le piézomètre Glib Tine (n° IRH 13984/5). Avec l'apparition des indices de surexploitation, une gestion contrôlée de la recharge et de l'exploitation de cette nappe a exigé une surveillance piézométrique mensuelle assurée par un réseau de six piézomètres.

Le piézomètre de Glib et-Tine (n° IRH 13984) a enregistré, entre le mois de septembre 1972 et celui de mars 2002 (30 ans), une baisse piézomètrique de 12,85m. Cette baisse est en rapport avec le débit d'exploitation de la nappe concernée (Figure 7.1). En effet, les observations mensuelles montrent que les remontées piézomètriques coïncident avec la diminution de l'exploitation pendant les périodes hivernales. Ces remontées sont plus amplifiées au cours des années pluvieuses.

Un ralentissement de cette baisse piézomètrique, est apparu à partir de l'année 1993 bien que le débit d'exploitation soit le plus important dépassant les 400 l s^{-1} entre 1994 et 1997. Par la suite, la baisse piézomètrique se continue avec la même pente malgré la sécheresse. La vitesse de cette baisse piézomètrique s'explique par la diminution de débit d'exploitation et la recharge introduite par les ouvrages de Conservation des Eaux et des Sols suite à certaines crues dispersées qui ont intéressé les bassins concernés durant cette période. La même tendance des fluctuations a été enregistrée par les autres piézomètres. Néanmoins, au niveau du piézomètre Koutine-5 (n IRH 8736/5), qui est le plus loin de la zone d'exploitation et le plus proche de la nappe des grès du Trias, la piézomètrie n'enregistre que des faibles fluctuations saisonnières.

Estimation de la recharge de la nappe par les eaux des pluies

Pour une surface d'alimentation de la nappe de Zeuss-Koutine de 785 Km^2 (Yahyaoui, 1997) et un coefficient d'emmagasinement de 14,4 10-4 (Ben Baccar, 1982), les volumes estimés des eaux des pluies qui ont infiltrées jusqu'à la nappe de Zeuss-Koutine suite aux épisodes pluvieux susmentionnés sont consignés dans le tableau suivant.

Tableau 7.4 *Estimation des volumes des eaux infiltrées jusqu'à la nappe de Zeuss-Koutine. (Années 1995, 1997 et 1998)*

Période	*Remontée piézo. (m)*	*V remontée piézo. (10^6 m^3)*	*V d'exploitation (10^6 m^3)*	*V entrant à la nappe (10^6 m^3)*
Sep/95 Avril/96	1,60	1,81	5,30	7,11 [1]
Sep/97 Avril/98	0,51	0,57	5,08	5,65 [1]
Sep/98 Nov/98	0,25 [2]	0,28	2,87	3,15 [1]

Note 1 : Une partie du ce volume provient par alimentation latérale à partir des nappes adjacentes.
Note 2 : La remontée se continue

7.4.2 *Variation du résidu sec de l'eau*

Une tendance d'augmentation de la salinité de l'eau au niveau de certains forages de la nappe de Zeuss-Koutine est apparue dès que l'exploitation a dépassé en 1982 un débit de 150 l s^{-1}. La variation de la salinité apparaît, depuis 1990, plus nette et significative suite aux prélèvements mensuels.

Aquifère du Crétacé inférieur

Au niveau du forage Zeuss-3 (n° I.R.H. 7413/5) captant l'horizon (B) du Sénonien inférieur et du Turonien entre 132 m et 207 m, la nappe est libre et elle est donc alimentée verticalement par les eaux des pluies (Figure 7.4). Le forage Zeuss-1 (n° I.R.H. 7241/5) captant l'horizon (A) du Sénonien inférieur entre 65 m et 344 m montre que la nappe est en charge (NS = + 3,5 m le 14/12/1962). Le toit imperméable de cet aquifère est constitué par les marnes et les argiles du Mio-Plio-Quaternaire (formation Zarzis).

Néanmoins, cet horizon aquifère est alimenté latéralement par l'intermédiaire des failles à partir de l'horizon (B). Les deux forages de Zeuss 1 et 3 captent des niveaux aquifères différents mais communicants par failles. L'horizon (B) se recharge verticalement par les eaux de pluies; l'horizon (A) se situe à 2 Km de cette zone d'alimentation.

Situés à quelques dizaines de mètres du forage Zeuss-1 (n° I.R.H. 7241/5), le forage Zeuss-1 bis (n° I.R.H. 7306/5) capte en trou libre, entre 476 m et 577 m, l'horizon (B) du Sénonien inférieur et un horizon du Turonien. La communication hydraulique de ce niveau aquifère profond, avec les autres niveaux qui lui sont superposés, est assurée par l'intermédiaire des failles et par drainance.

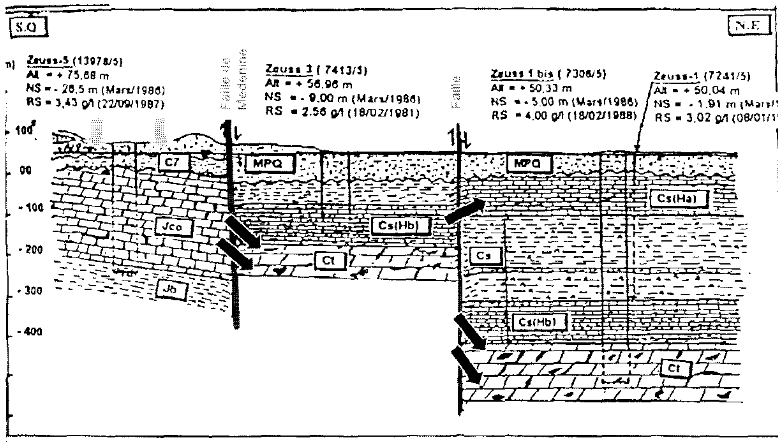

Figure 7.4 *Corrélation Lithostratigraphique et hydrogéologique le long d'oued Zeuss.*

Le suivi mensuel de la salinité de l'eau depuis 1984 au niveau des forages d'oued Zeuss fortement sollicités, a permis de déceler une tendance franche d'homogénéisation de la salinité de l'eau des différents niveaux aquifères de Zeuss-Koutine (Figure 7.5a).

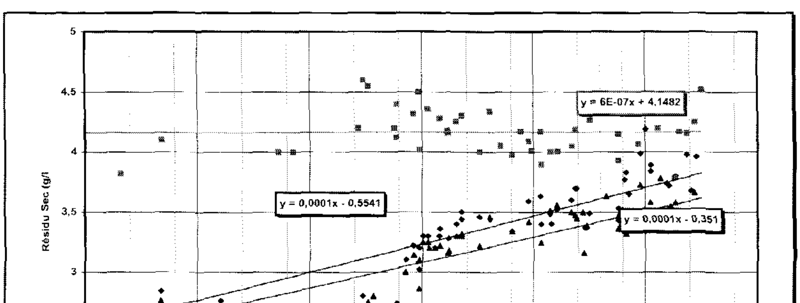

Figure 7.5[a] *Suivi mensuel de la salinité: Aquifère du Crétacé Inférieur*

En effet, au sein des niveaux aquifères du Sénonien inférieur de l'horizon (B), qui sont les plus profonds, les plus salés et les moins rechargés au niveau du forage Zeuss-1bis (n° IRH 7306/5), la salinité a demeuré quasi-stationnaire dans l'ensemble avec une fluctuation du résidu sec de 500 g l^{-1} en rapport avec l'exploitation. Toute fois, on en enregistre une tendance de diminution entre 1987 et 1993 dont la valeur moyenne est d'environ 52 mg l^{-1} an^{-1}. Cette diminution traduit une alimentation croissante provenant des niveaux aquifères moins profonds et moins salés (horizon A) par l'intermédiaire des failles et par drainance.

Par contre, pour les niveaux les moins chargées en sels et bénéficiant d'une meilleure recharge à partir des eaux des pluies (horizons A et B), la salinité de l'eau augmente d'une année à l'autre (Zeuss-1 n° I.R.H. 7241/5 et Zeuss-3 n° IRH 7413/5). Le taux d'augmentation moyen entre 1971 et 2002 est de 36 mg l^{-1} an^{-1}. Ceci permet de conclure qu'au cours de l'exploitation, la salinité des eaux les moins chargées en sels provenant de l'infiltration des eaux ruisselées diminue, alors que celle provenant des niveaux aquifères profonds sous-jacents à salinité élevée, augmente.

Pour ces trois forages, les fluctuations saisonnières de la salinité reflètent la variation de débit de pompage, ainsi que l'influence des épisodes pluvieux qui sont à l'origine de la recharge de la nappe.

Aquifère du Jurassique

La géométrie et la nature de l'aquifère, constituent avec le mode d'alimentation et le débit de prélèvement, les principaux facteurs qui conditionnent l'évolution de la salinité. (Figure 7.5[b])
Le forage Zeuss-4 (n° I.R.H. 13100/5) est situé à proximité du forage Zeuss-5 (n° I.R.H. 13978/5) sur la berge de l'oued Zeuss. Ce forage capte, en trou libre et entre 139 m et 165 m, une nappe libre logée dans les calcaires du Jurassique supérieur. Le bassin versant d'oued Zeuss et en particulier aux environs du forage Zeuss 4 est quasi-totalement aménagé par des seuils en gabion et par des banquettes en terre dans les talwegs et les petits cours d'eau.

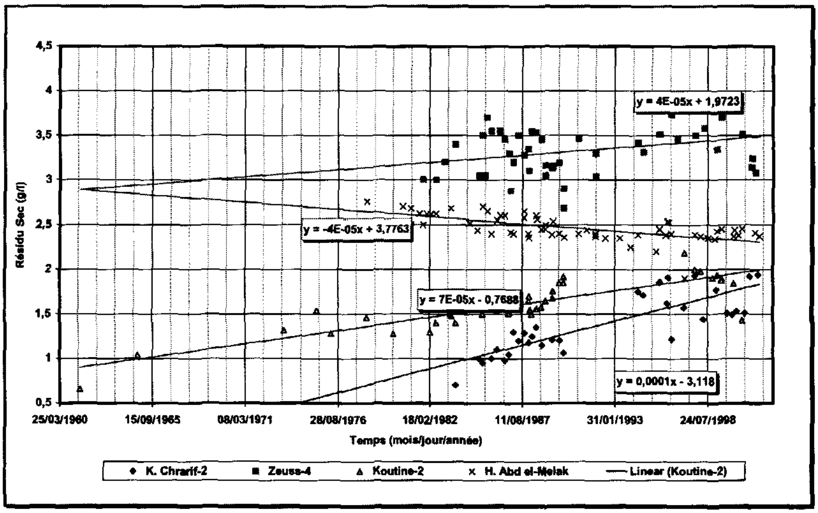

Figure 7.5[b] *Suivi mensuel de la salinité: Aquifère du Jurassique*

L'évolution de la salinité de l'eau marque à ce niveau des diminutions durant les épisodes pluvieux contribuant à la recharge de la nappe et des augmentations durant les périodes sèches. La marge des fluctuations varie de 0,5 g l^{-1} à 1 g l^{-1} et la résultante de l'évolution a marqué une tendance d'augmentation de 15 mg l^{-1} an^{-1}. Ce comportement géochimique dépend étroitement de la pluviométrie et de l'exploitation.

Le forage Hessi Abd Malek (n° I.R.H. 13019/5) capte en trou libre entre 10 m et 249 m les calcaires du Jurassique supérieur qui sont discordants sur les grès du Trias inférieur et moyen.

La baisse de la salinité de l'eau en fonction du temps et de l'exploitation au niveau de ce forage montre, d'une manière indéniable, l'alimentation des calcaires du Jurassique à partir de la nappe des grès du Trias, dont la salinité varie dans la région de Tajera entre 1 g l^{-1} et 2 g l^{-1}. La diminution engendrée est d'environ 15 mg l^{-1} an^{-1}.

Les forages Kaçar Chrarif (n° I.R.H. 16708/5 et Koutine (n° I.R.H. 7193/5): Les bassins versants des oueds Koutine et Zigzaou, au sein desquels se trouvent les deux forages Kaçar Chrarif et Koutine sont traités quasi-totalement par les travaux de Conservation des Eaux et des Sols. Ces deux forages captent en trou libre l'aquifère du Jurassique supérieur qui se recharge directement à partir des eaux de ruissellement.

Entre 1982 et 2002, la surveillance de la chimie de l'eau de la nappe a montré une augmentation graduelle de la salinité au niveau de deux forages avec un taux d'augmentation qui varie de 26 $mg^{-1}l^{-1}$ an^{-1} à 37 mg l^{-1} an^{-1}. Cette évolution géochimique met en évidence un phénomène d'échange vertical de la salinité. En effet, le pompage épuise graduellement les eaux relativement douces résultant de l'infiltration des eaux de surface. Ce pompage fait apparaître un cône de dépression qui favorise la remontée des eaux profondes salées. Ce qui entraîne une augmentation graduelle du débit provenant des réserves géologiques de la nappe.

7.5 Simulation numérique de la nappe de Zeuss-Koutine

Avec une augmentation des besoins en eau pour les divers usagers et étant donnée l'aridité du climat du sud-est Tunisie, la nappe profonde de Zeuss-Koutine est excessivement sollicitée. Le modèle numérique constitue un meilleur outils d'établissement du bilan de cette nappe en fonction des facteurs naturels et provoqués du milieu. C'est aussi un moyen quantitatif prévilligié d'une gestion ultérieure rationnelle et contrôlée.

7.5.1 Construction du Modèle

Le Modèle mathématique de cette nappe a été réalisé à l'aide du logiciel Multic (Djebbi 1992). Ce logiciel est conçu pour assurer la simulation numérique des transferts de pression en régime permanent ou/et transitoire dans les aquifères multicouches de forme quelconque en mailles carrées régulières.

La première étape de la construction du modèle consiste à définir la géométrie du réservoir aquifère, les conditions aux limites du modèle à la discrétisation du domaine d'étude en mailles carrées homogènes et à la préparation des données nécessaires aux calages des régimes permanent et transitoire.

Géométrie du réservoir aquifère

La nappe de Zeuss-Koutine est logée dans un système aquifère comportant plusieurs compartiment communiquant essentiellement par failles (section 7.2). L'ensemble de ce système peut être assimilé à un seul aquifère.

Conditions aux limites
La nappe de Zeuss-Koutine est limitée à l'ouest par les affleurements argileux et dolomitiques du Cénomanien inférieur à moyen au niveau de la falaise de Matmata, au sud et au sud-ouest par la nappe des grès du Trias dont l'écoulement souterrain se fait vers le nord-est et qui communique avec la nappe de Zeuss-Koutine à travers les failles et par l'intermédiaire de la discordance de Sidi Stout. Au sud-est, elle est limitée par la faille de Medenine et à l'est par l'effondrement des formations aquifères du Crétacé et du Jurassique de plusieurs centaines de mètres sous les dépôts tertiaires.

Limites à débits imposés
Il s'agit :

- des limites nord-ouest, ouest et sud-ouest répresentés par les affleurements des horizons aquifères du Cénomanien au niveau des relièfs de Matmata,
- de la limite sud-ouest correspondant au contact des grès du Trias avec les calcaires fissurés de l'albo-aptien et du Jurassique supérieur,
- des zones schématisées par les lits d'oueds qui contribuent à l'alimentation de la nappe envisagée par infiltration des eaux surface.

Limites à potentiels imposés
Elle correspond à la zone d'exutoire de la nappe à la limite est de celle-ci.

Choix du maillage
La configuration hydrogéologique de l'aquifère de Zeuss-Koutine (Figure 7.6) montre que le modèle de la nappe peut avoir une représentation schématique à une seule couche. Le domaine d'étude a été subdivisé en 725 mailles carrées régulières de 1km de côté (Derouiche,1997).

7.5.2 Calage du modèle en régime permanent

Pour faire le calage du modèle en régime permanent, il suffit d'estimer les paramètres régissant l'écoulement permanent (transmissivité, alimentation) tout en essayant de réduire les écarts entre les valeurs observées et calculées de la charge hydraulique à une valeur inférieure à une limite préalablement fixée.

L'état de la piézométrie en 1974, matérialisant la situation d'un écoulement permanent de la nappe, a été fixé comme référence au modèle pour deux raisons suivantes ; i) les premières mesures piézométriques dont on dispose datent de 1974. ii) l'exploitation de la nappe profonde n'a pris d'importance qu'à partir de 1974 avec la mise en service des forages.

La carte des valeurs initiales de transmissivités à introduire dans le modèle a été obtenue par interprétation et comparaison avec les valeurs mesurées à partir d'essais de pompage. Cette carte donne les valeurs moyennes de la transmissivité (en $m^2 s^{-1}$) sur l'ensemble des aquifères captés.

Pour simuler la contribution du réseau hydrographique à l'alimentation de la nappe, les niveaux piézométriques observés ont été imposés ainsi que le débit d'alimentation de la nappe à partir de l'infiltration des eaux de ruissellement qui a été estimé à 283 $l\ s^{-1}$. La précision de ces valeurs a été améliorée par ajustements successifs au cours des opérations du calage du modèle.

Concernant la contribution des eaux pluviales dans l'infiltration directe, elle a été estimée à 4 $l\ s^{-1}$ au niveau des reliefs des Matmatas et pratiquement nulle sur le reste du domaine d'étude. Quant au débit transitant de la nappe du Trias vers la nappe de Zeuss-

Koutine, il a été ajusté à une valeur de 36 l s^{-1}. Ainsi, les ressources de la nappe de Zeuss-Koutine ont été évaluées à un débit total de 323 l s^{-1}.

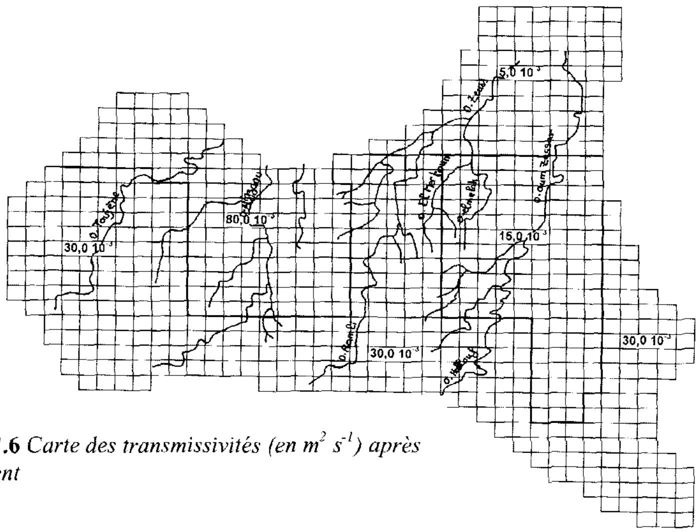

Figure 7.6 *Carte des transmissivités (en m^2 s^{-1}) après ajustement*

Le calage du modèle en régime permanent a porté sur la répartition des transmissivités et le contrôle de la validité de ce calage, s'est fait sur la totalité des mailles.

L'écart de calage maximal entre les charges hydrauliques calculées et celles mesurées atteint en moyenne ± 0,54 m. Les transmissivités retenues après le calage du modèle en régime permanent sont représentées par la figure 7.6. En concordance avec la nature des séries calcaires caractérisées par une fissuration importante au niveau de l'aquifère du Jurassique, les transmissivités fixées par calage sont élevées dans la partie en amont du bassin versant de l'oued Zigzaou. Aussi on peut observer ces fortes valeurs de transmissivités au niveau du forage Henchir Frej qui capte l'aquifère de l'Apto-Cénomanien.

Tableau 7.4 *Bilan en eau en régime permanent.*

Entrées	Infiltration directe aux reliefs des Matmatas	4	l s^{-1}
	Infiltration à partir du réseau hydrographique	283	l s^{-1}
	Contribution de la nappe du Trias	36	l s^{-1}
	Total	323	l s^{-1}
Sorties	Prélèvement par forages	102	l s^{-1}
	Ecoulement souterrain vers l'exutoire	221	l s^{-1}
	Total	323	l s^{-1}

7.5.3 Simulation de l'écoulement en régime transitoire

Sur la base de l'historique piézomètrique disponible, la simulation en régime transitoire consiste à reproduire le fonctionnement hydrodynamique de la nappe pendant les 25 dernières années (1975/2000). On a fixé 64 phases de calcul avec un pas de temps annuel entre 1975 et 1991 et un pas variable de 1 mois à 6 mois pour le reste de la période. Pour évaluer les débits d'alimentation de la nappe, on a calculé lors de chaque phase, le coefficient d'alimentation en maintenant la contribution de la nappe du Trias égale à 36 l s^{-1} (Derouiche, 1997). Ce *coefficient est calculé en ramenant la pluviométrie enregistrée pendant* la *phase* à la pluviométrie interannuelle de la zone qui est de 196.8 mm.

Concernant l'exploitation de la nappe en régime transitoire, elle est donnée pour chaque phase tout en essayant de subdiviser l'année en deux périodes : une période estivale s'étendant du mois de mars au mois de septembre où l'exploitation est maximale et une période hivernale s'étendant du mois d'octobre au mois de février où l'exploitation est minimale.

Le calage en régime transitoire consiste à vérifier le fonctionnement hydraulique du modèle par phase en agissant sur les paramètres hydrauliques, notamment le coefficient d'emmagasinement (Grove and Stollenwerk, 1984). Le coefficient d'emmagasinement retenu après calage est égal à 15.10^{-3}. En faisant la comparaison entre la piézométrie simulée après le calage et celle observée au niveau des six pièzomètres de contrôle (Henchir Frej, Zeuss1, Ksar Chrarif1, Ksar Chrarif2, Glib-Ettine, et Hassi Abdel Malek), on obtient un écart maximum de 6 m au niveau de Ksar Chrarif-2 (Figure 7.7[a]).

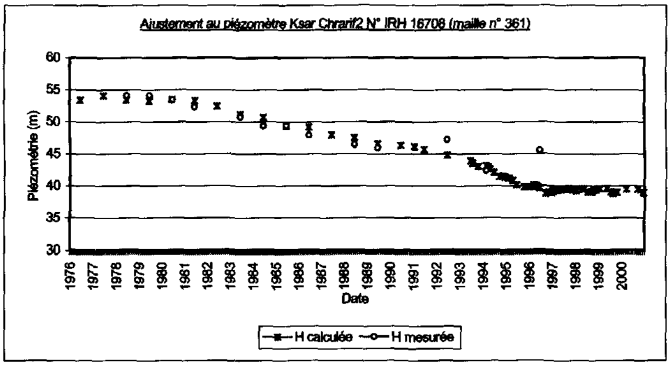

Figure 7.7[a] *Ajustement aux piézomètres Ksar Chrarif*

Concernant le piézomètre de Glib Ettine, il est le seul piézomètre qui présente des mesures piézométriques pendant la période (1974-2000). Son calage durant cette période a donné un faible écart entre la piézomètrie mesurée et celle calculée.

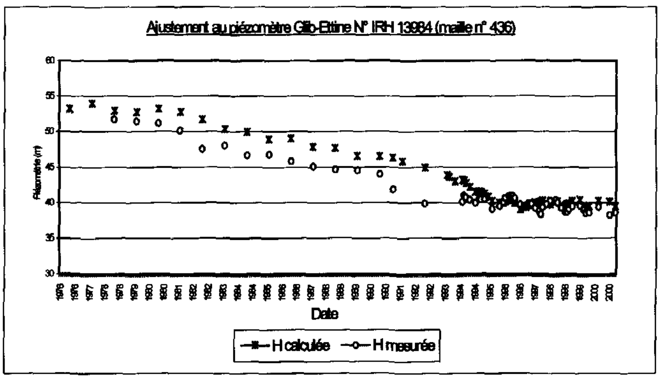

Figure 7.7[b] *Ajustement aux piézomètres Glib-Ettine*

En comparant les résultats du bilan calculé de la nappe relatifs aux trois années (Tableau 7.5), on constate que : i) en 1975 (Bassins peu traités par des travaux de C.E.S), les entrées ne sont que de 285 l s^{-1}, ii) en 1996 (travaux de CES en cours) les entrées deviennent de 301 l s^{-1}, iii) en 2000 (après achèvement des travaux des ouvrages de recharge) les entrées de la même nappe arrivent à 447 l s^{-1}. Ainsi, il y a une nette augmentation de débit d'alimentation de la nappe en fonction de l'avancement des travaux de CES.

Tableau 7.5 *Bilan en eau en régime transitoire (1975, 1996 et 2000).*

Année		*1975*	*1996*	*2000*
Entrées	Infiltration directe aux reliefs des Matmatas (l s^{-1})	4	4	4
	Infiltration à partir du réseau hydrographique (l s^{-1})	285	302	448
	Contribution de la nappe du Trias (l s^{-1})	36	36	36
	Total (l s^{-1})	325	342	488
Sorties	Prélèvement par forages (l s^{-1})	123	421	345
	Ecoulement souterrain vers l'exutoire (l s^{-1})	202	161	154
	Total (l s^{-1})	325	582	499

D'autre part l'exploitation de la nappe a diminué après avoir atteindre son maximum en 1996 (421 l s^{-1}) pour avoir une valeur de 345 l s^{-1} en 2000. La carte des rabattements piézométriques pour l'année 2000 par rapport à l'année de référence (1974) nous illustre un rabattement maximum de 15 m au niveau du bassin versant d'oued Zigzaou (Figure 7.8).

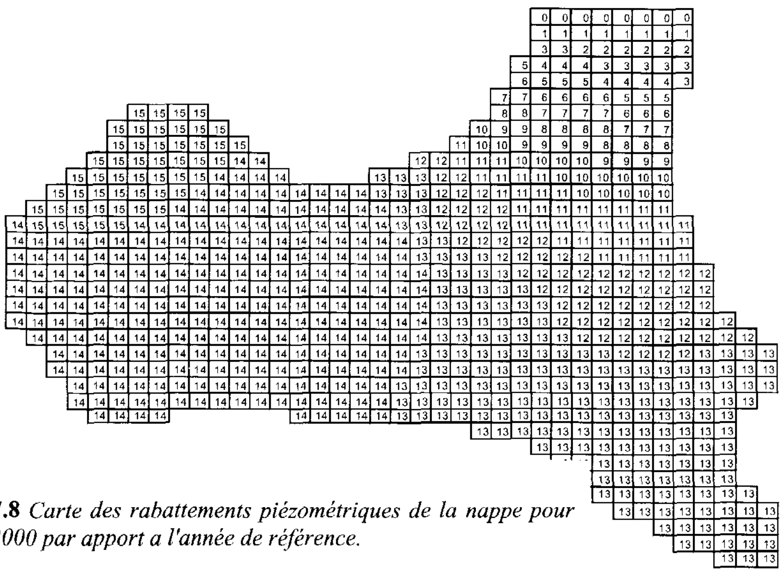

Figure 7.8 *Carte des rabattements piézométriques de la nappe pour l'année 2000 par apport a l'année de référence.*

7.5.4 Calcul des apports infiltrées jusqu'à la nappe des ouvrages C.E.S

Depuis 1985, les bassins versants de la nappe de Zeuss-Koutine ont été aménagés à fin de:

- Assurer un apport supplémentaire à la nappe en favorisant davantage l'infiltration des eaux de ruissellement.
- Amortir l'abaissement continu de la piézomètrie de cette nappe
- Augmenter ses ressources dynamiques à fin de satisfaire aux besoins en eau potable de la région.
- Ralentir la dégradation de la qualité chimique des eaux souterraines.
- Lutter contre l'érosion hydrique.

L'étude du projet de recharge de la nappe de Zeuss-Koutine par la maîtrise des eaux de surface a avancé une valeur d'apport théorique supplémentaire induit qui est de l'ordre de 125 l s^{-1}, ce qui correspond à 3,9 Mm3 an^{-1}. Or, il a été supposé qu'à peu prés 40 % de ce débit (50 l s^{-1}) soit perdu par ruissellement en cas d'apports dépassant la capacité de rétention des ouvrages de C.E.S ou par écoulement hypodermique. Il s'ensuit que seulement 70 % des apports arrivent jusqu'à la nappe, ce qui lui permet de bénéficier d'un apport supplémentaire évalué à 50 l s^{-1} (Mansouri, 1985).

Le modèle numérique de la nappe de Zeuss-Koutine a fournit, après son calage en régime transitoire, les apports moyens annuels à la nappe. La figure 7.9 donne les apports annuels à la nappe calculés par le modèle, la pluviométrie annuelle de la région et la moyenne de l'alimentation de la nappe avant et après l'année 1990.

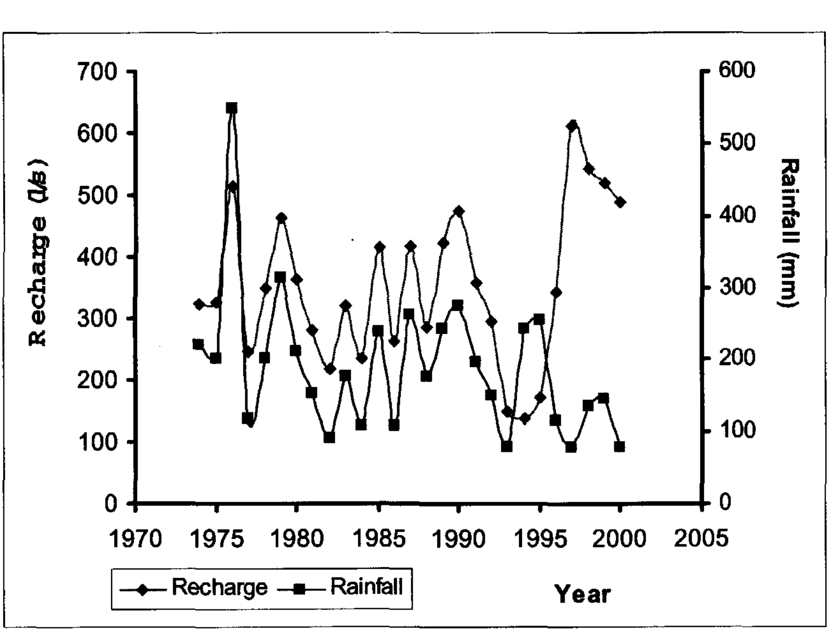

Figure 7.9 *Apports annuels à la nappe de Zeuss-Koutine*

L'examen de la figure 7.9 montre que l'apport moyen à la nappe pendant la seconde période (après 1990) est nettement inférieur à la moyenne annuelle des apports. Ceci ne nous permet pas d'en tirer une conclusion quant à la quantification de la contribution des aménagements de C.E.S à l'alimentation de la nappe.

Il faut donc comparer les apports des années à événements pluviométriques comparables. En effet, pendant les deux années hydrologiques 1983/84 et 1991/92, durant lesquelles l'apport pluviométrique était respectivement de 146.8 mm et 151.5 mm, on a enregistré durant 3 jours un cumul pluviométrique de 52.9 mm pour l'année 83/84 et 45 mm pendant 2 jours pour l'année 91/92. Si on compare les apports de la nappe pour ces deux années, on trouve que la nappe a pu bénéficier d'un apport supplémentaire de 60 l s^{-1} retenu par les travaux d'aménagement des bassins versants. La contribution de ces ouvrages de recharge se fait sentir surtout pendant les épisodes à pluies torrentielles.

En outre, pour les deux années 1992 (début de la stratégie de C.E.S) et 1999 (achèvement des travaux de C.E.S) durant lesquelles la pluviométrie était respectivement, de 150 mm et 143.8 mm, l'apport annuel à la nappe a augmenté de 76.5%. Ce qui montre, encore une fois, l'importance des apports supplémentaires introduite à la nappe au moyen des ouvrages de C.E.S.

7.6 Conclusion

La nappe de Zeuss-Koutine est logée au sein de plusieurs compartiments aquifères recelant des eaux des salinités différentes. La surexploitation de cette nappe pour l'alimentation en eau potable des principales agglomérations du sud-est Tunisie depuis 1974 a entraîné une baisse piézomètrique de 12,85 m et une homogénéisation de la salinité de différents niveaux aquifères tendant vers une augmentation et notamment au niveau des aquifères superficiels rechargés par les eaux de ruissellement.

Cet état de surexploitation a été soulagé par le dessalement et l'exploitation des eaux saumâtres de la nappe du Mio-Plicène de la Jefara à partir de l'année 1998.

La recharge provoquée par les travaux de Conservation des Eaux et Sols de la nappe envisagée constitue une expérience encourageante d'amélioration de potentiel en eau souterraine des nappes rechargeables dans un climat aride comme celui du sud-est Tunisie.
Les réseaux d'observation d'évolution de l'exploitation, de la chimie et de la piézomètrie ont constitué un outil fondamental d'évaluation de cette évolution. Le modèle numérique représente un moyen avancé de quantification et de prévision d'une gestion rationnelle et contrôlée de cette nappe.

Sachant que la nappe de Zeuss-Koutine fait partie d'un système plus important rassemblant la totalité des nappes de la Jefara tunisienne et libyenne, il est important d'introduire l'étude hydrogéologique et la modélisation de cette nappe dans le cadre du projet d'Observatoire du Sahara et du Sahel (OSS) qui construit actuellement un modèle hydrogéologique du Système Aquifère du Sahara Septentrional (SASS), groupant la Tunisie, l'Algérie et la Libye. Ceci permettra au mieux de réajuster le bilan de la nappe concernée.

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Part III :

Economic analysis and decision-making for water harvesting

8 ECONOMIC EVALUATION OF THE ON-SITE IMPACT OF WATER HARVESTING IN SOUTHERN TUNISIA

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Abstract

Water harvesting techniques (WHT) play an important role in water resources conservation in (semi-) arid environments. Hydrological studies can give insight in the impact of WHT, both at local (on-site) and downstream (off-site) scale. However, hydrological research alone does not allow for a complete assessment of the impact of WHT, as it does not study the human dimension of water management. This paper takes soil water balance studies as a starting point to translate physical effects of WHT in economic terms. Focusing on on-site effects, methods are described and applied.

For one of these situations, a *jessr* unit in southern Tunisia, an economic evaluation is made. The most important physical effect of this WHT is increased water availability to tree crops. This increased water availability is translated in effects on olive yield. Apart from the benefits from olive yield, detailed accounts are also presented for both costs and other benefits. Subsequently the jessr is evaluated using financial and economic cost-benefit analysis.

The case clearly shows what data are required to evaluate WHT at local level. Difficulties and assumptions are discussed and it is concluded that on-site effects alone might not justify investment in construction of WHT.

Keywords: water harvesting, impact assessment, economic evaluation, *Olea europeae*, Tunisia, jessr

8.1 Introduction

Water harvesting techniques (WHT) play an important role in water resources conservation in (semi-)arid environments. In many semi-arid and arid regions in Mediterranean countries, such as southern Tunisia, the geographical focus of this paper, WHT have a long history and governments have supported their expansion in recent years (e.g. Stratégie Nationale de Conservation des Eaux et Sols in Tunisia). Government support has been based on the assumption that storing water for present and/or future use in the soil profile or the groundwater is per definition better than losing it to the sea. However, not many detailed analyses have been documented about the economic evaluation of WHT, neither for farmer investment nor for large-scale governmental programmes (e.g. Fox and Rockström, 2000; Panigrahi *et al.*, 2001).

Hydrological studies can give insight in the impact of WHT on the soil water balance, both at local (on-site) and downstream (off-site) scale. However, hydrological research alone does not allow for a complete impact assessment of WHT, as it does not study the human dimension of water management. This paper takes soil water balance studies (Schiettecatte *et al.*, Chapter 5) as a starting point to translate physical effects of WHT in economic terms.

Focusing on on-site effects, methods are described and applied to a real-world situation in southern Tunisia.

8.2 Materials and Methods

8.2.1 Description of research site and physical measurements

The research site was installed at a jessr unit (plural: *jessour*), a WHT consisting of an impluvium (8 ha, slope 10-70%), a terrace (0.275 ha, slope <1%) and a dike with a spillway to evacuate surplus water. The jessr, named 'Amrich' after its owner, is located on the slopes of the Matmata Mountains in the upstream section of the Oued Oum Zessar catchment area (367 km^2) in southern Tunisia, within the Governate of Médenine. The climate is arid, with very erratic precipitation. Average precipitation (1967-1994) in the Matmata Mountains amounts to 240 mm y^{-1} (Ouessar *et al.*, 1999). Rainfall probability is highest from November to March. Land use at the jessr terrace is 'arboriculture', with 5 olive trees (approximately 50 years of age) and 1 fig tree representative for the dominant position of the olive tree in the area, making up at least 75% of the total number of trees. In the wetter years cereals (barley, wheat) are also cultivated.

Texture of the terrace was classified as sandy loam. Various field measurements were carried out and Time Domain Reflectometry (TDR) was used to monitor soil moisture content (2000-2001) at the terrace in 4 access tubes at depth intervals of 20 cm. Assuming a rooting depth of 1.4 m, maximum available soil water that can be stored in the soil profile (ASW max) was estimated at 293 mm. Volumetric water content at permanent wilting point (pF = 4.2) was 9%. Precipitation and rainfall intensity data were collected from the automatic tipping-bucket pluviograph at Chouamek (1998-2001), at a few kilometres from the research site. Additional precipitation analyses were undertaken with meteorological data from Beni Khédache (1969-2000) at a distance of 10 km. Potential evapotranspiration (Penman-Monteith) was calculated from data of the meteorological station of Médenine (1985-1995) at 35 km from the research site (Ouessar *et al.*, 1999; Tanghe, 2002).

8.2.2 Impact assessment methodology

The impact assessment methodology consisted in a translation of the effect of increased water availability on crop productivity. For this purpose, use was made of a spreadsheet water balance model (De Graaff, 1996). A test of the methodology was first carried out with available data for Chaal, near Sfax (Ben Rouina, 1994). For Amrich jessr, run-on events were integrated into the water balance simulation model assuming the dry infiltration characteristic (Tanghe 2002).

In determining the effect of increased water availability on crop productivity, first the relationship between water-stress and yield had to be established. For this purpose, the FAO method (Allen *et al.*, 1998), developed for annual crops, was adapted for olive. The relationship between water-stress and olive tree productivity is much less straightforward as is the case for annual crops, because many factors come together in determining olive yield and it is not easy to separate each effect. However, in literature there is general consensus that a good water supply throughout the growing period leads to higher yields and less pronounced alternate bearing. Tombesi *et al.* (1996) present a qualitative overview of the effects of water-stress.

In the FAO approach, maximum evapotranspiration (ET_m) is first calculated by multiplying reference evapotranspiration (ET_0) with the so-called crop factor (kc). Penman-Monteith method and corresponding kc factors were used. The crop factor depends on crop characteristics concerning evapotranspiration and on the coverage of the canopy. Doorenbos and Kassam (1979) give an average yearly value of kc of 0.4-0.6 for olive. However, kc-values vary over the year as a result of development stage and other crop and climatic characteristics. Dettori (1987), Michelakis *et al.* (1996), Pastor *et al.* (1998) and Villalobos *et al.* (2000) provide monthly kc-values. Intra-annual fluctuations are not so much related to ground cover, as in annual crops, but reflect changes in metabolism activity and radiation use efficiency. For the water balance simulations of Chaal and Amrich, kc-values were reduced to compensate for low ground cover and suggested adaptation of local varieties to arid conditions (Table 8.1). Actual crop evapotranspiration (ET_a) is calculated from ET_m; depending on the available soil moisture and the precipitation balance linear or exponential depletion of soil moisture occurs (De Graaff, 1996).

The next step consists in estimating yield response to water-stress. Widely used is the equation for the relation between yield and crop evapotranspiration developed by Doorenbos and Kassam (1979) by defining a yield response (ky) factor that relates the ratios actual/maximum evapotranspiration and actual/maximum yield to each other. They give ky-factors for a wide range of crops, but not for olive. Olive yield has low sensitivity to water supply, what could be interpreted as a ky-factor of 0.70-0.80. In reality, the ky-factor varies through the year, with periods of high sensitivity accounting for above-average ky-values and vice versa. Remarkably, while much research has been conducted and published on olive water requirements, almost no attempts were made to evaluate the effect of water-stress on olive yields, and in only one case ky-values were presented for olive (De Graaff, 1996). For the present study, yield response to water-stress was divided into a fruiting yield response factor ky_{fruit} and a vegetative yield response factor ky_{veg}, respectively in analogy to the effects identified on the yield in year n and the yield in year n+1 (Boulouha, 1995; Tombesi *et al.*, 1996). Hence, the single relationship established by Doorenbos and Kassam (1979) was slightly altered and split in two (Equation 1 and Equation 2). Equation 1 determines the effect of water stress on fruit yield within the same year:

$$\left(1-\frac{Y_{a\text{-}fruit(n)}}{Y_{m\text{-}fruit(n)}}\right)=ky_{fruit}\cdot\left(1-\frac{ET_{a(n)}}{ET_{m(n)}}\right) \qquad \text{(Equation 1)}$$

Where:

$Y_{a\text{-}fruit(n)}$ = actual harvested fruit yield in year n;
$Y_{m\text{-}fruit(n)}$ = maximum harvested fruit yield in year n (calculated in equation 2)
ky_{fruit} = fruiting yield response factor;
$ET_{a(n)}$ = actual evapotranspiration in year n
$ET_{m(n)}$ = maximum evapotranspiration in year n

In Equation 1 the parameter $Y_{m\text{-}fruit(n)}$ is unknown and can be calculated with:

$$\left(1-\frac{Y_{m\text{-}fruit(n)}}{Y_{m(n)}}\right)=ky_{veg}\cdot\left(1-\frac{ET_{a(n-1)}}{ET_{m(n-1)}}\right) \qquad \text{(Equation 2)}$$

Where:

Y_m = maximum yield in year n as determined by tree age and yield consistency index
ky_{veg} = vegetative yield response factor

$ET_{a(n-1)}$ = actual evapotranspiration in year n-1
$ET_{m(n-1)}$ = maximum evapotranspiration in year n-1

Equation 2 comprises the relation between water stress in year n-1 (causing reduced vegetative growth) and its effect on the maximum yield $Y_{m\text{-}fruit(n)}$ in year n. From the above it follows that each year, water-stress can result in yield reduction still during the same year (as a consequence of ky_{fruit}), or during the next year (as a consequence of ky_{veg}). Any simulation will thus require an initial value for ky_{veg}. Table 8.1 shows tentative values for the respective yield response factors.

Simultaneously, alternate bearing is considered by introducing the concept of Yield Consistency Index (YCI). The YCI is a measure for the natural and variety-endogenous tendency to produce coherent yields, disregarding water, nutrient or other environmental factors and pests and diseases. It is defined as the ratio between a characteristic, non-limited yield in an 'off'-year and on'-year and can theoretically vary between 0 and 1. Annual national data series of olive yields and olive (oil) production (Loussert and Brousse, 1978; FAOSTAT, 2001; Comete engineering, 1996; INS, 1995; DG/PDIA, 1995) were used to arrive at YCI estimates ranging from a minimum of 0.58 ± 0.21 to a maximum of 0.71 ± 0.22. In these data series, variability was assumed to be rather insensitive to climatic factors. On the contrary, local data (Trigui, 1994) yielded a much lower YCI-estimate of 0.25 ± 0.28, reflecting both variability of climatic and genetic origin. For the impact assessment simulations, a value of YCI = 0.60 is assumed.

Finally, maximum (potential) yield to be used in calculations was related to tree age. In traditional olive cultivation, it takes about 6 years (irrigated) to 12 years (rainfed) before olive trees become productive (CNEA, 1996). Assumed is that for olive trees on the jessr terraces it takes 6 years before production starts.

Table 8.1 *Olive development stages and values of crop and yield response factors for southern Tunisia.*

Month	*Development stage*	*Vegetative growth*	*Fruit growth*	*kc*[1] *Amrich*	*kc*[1] *Chaal*	ky_{veg}	ky_{fruit}
January	Dormant	Resting/dormant		0.40	0.30	0.00	0.60
February	Dormant	Resting/dormant		0.40	0.30	0.00	0.60
March	Initial	Resting/dormant	Bud differentiation	0.55	0.25	0.00	0.60
April	Development	Active		0.50	0.20	0.70	0.80
May	Development	Active	Flowering	0.45	0.20	0.70	0.90
June	Development	Active		0.40	0.20	0.50	0.60
July	Mid Season	Reduced	Yield formation	0.35	0.20	0.00	0.70
August	Mid Season	Reduced	Stone hardening	0.35	0.25	0.00	1.00
September	End	Active	Yield formation	0.45	0.25	0.30	0.70
October	End	Active	Yield formation	0.50	0.25	0.70	0.60
November	End	Resting/dormant		0.45	0.25	0.00	0.60
December	Dormant	Resting/dormant		0.40	0.30	0.00	0.60

Note 1: kc-values for the two areas reflect differences in tree density and consequently ground cover.

8.2.3 *Economic evaluation methods*

Both financial CBA (Cost-Benefit Analysis) and economic CBA were used. The financial CBA focuses on the benefits to farmers of investing in WHT. Evaluation criteria used were the Net Present Value (NPV) and the Internal Rate of Return (IRR). In this analysis only on-site effects are considered. A comparison is made between the without case (livestock grazing only) and the case with construction of WHT (combination of livestock grazing on the impluvium and cultivation of the terrace area). Thus, water harvesting allows intensified land use and yield increase of crops grown. Quantification of these effects involved monetary valuation of the effects determined in the impact assessment. Farm gate prices were collected from rural markets and from interviews with farmers. All prices are expressed in Tunisian Dinars (TD).

An appropriate time horizon was set at 30 years, as the benefits which accrue to investing in water harvesting in general and tree production in particular appear only after several years. However, the physical and economic life of WHT may well be over 50 years. The reason for not considering the period from 30-50 years after investment is that the social time preference, expressed by the high discount rate used (10.8% according to the Central Bank of Tunisia, 1997), gives only very marginal importance to benefits expected on the very long term.

Sensitivity analyses to climatic risk were carried out by considering different sequences of three types of years (dry, average and wet) leading to different effects on yield and consequently to different financial returns.

In the economic CBA accounting prices are used. All other factors remain the same as in the financial CBA.

8.3 Results

8.3.1 Impact assessment of on-site productivity

The developed methodology results in a more complex description of the relationship between water-stress and yield, which is thought to be more realistic than the conventional approach with a single ky-factor and without considering alternate bearing. It was tested for a 5 year data-set of Chaal, Sfax region (Ben Rouina, 1994). Water balance could be well simulated with the spreadsheet model, except for months with high rainfall, probably due to the underestimation of runoff (Figure 8.1). Simulated olive yields matched measured yields well (r^2=0.94) (Table 8.2).

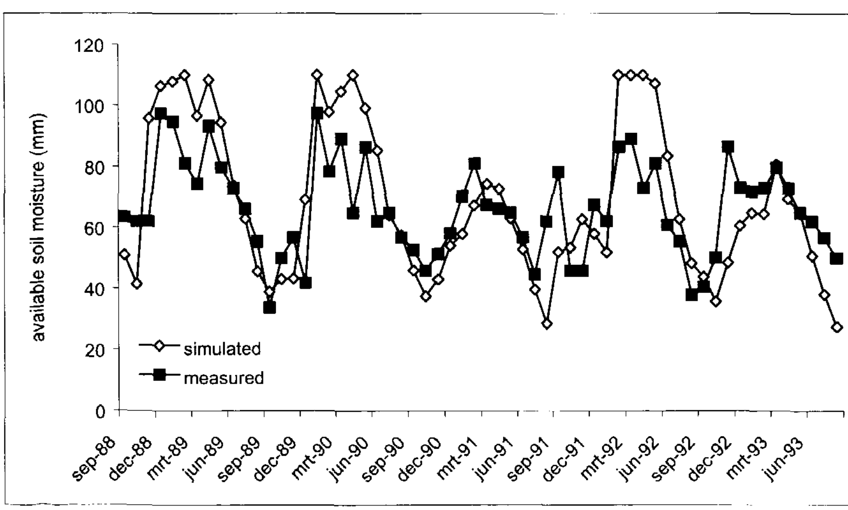

Figure 8.1 *Simulated and measured available soil moisture in a 1.1 m profile during 5 years at Chaal, Sfax area.*

The water balance simulation model was also applied to Amrich jessr, based on rainfall data at Chouamek and reference evapotranspiration at Médenine (Figure 8.2). Only during a small period (January 2000 – August 2001) could the simulated values be compared to measured data (Figure 8.3). During this exceptionally dry period, only one run-on event occurred for sure (31 May 2001). It seems that the run-on that should have occurred in October 1999 according to the rainfall data of Chouamek did not take place at Amrich and vice-versa the increased soil water content measured during March and June 2000 was not simulated. These differences could be due to high local rainfall variability. In Figure 8.3 two simulations are presented, respectively based on a maximum ASW in the terrace soil profile of 293 mm (a) and 168 mm (b). While the first value was derived from measurements, the second was derived from literature (De Graaff, 1996) and shows a better fit to measured available soil moisture content.

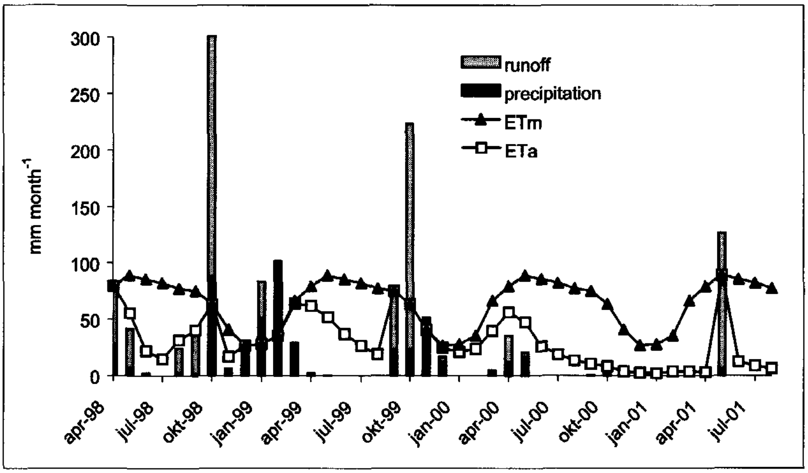

Figure 8.2 *Monthly precipitation (Chouamek) and run-on, and maximum and actual evapotranspiration on Amrich terrace.*

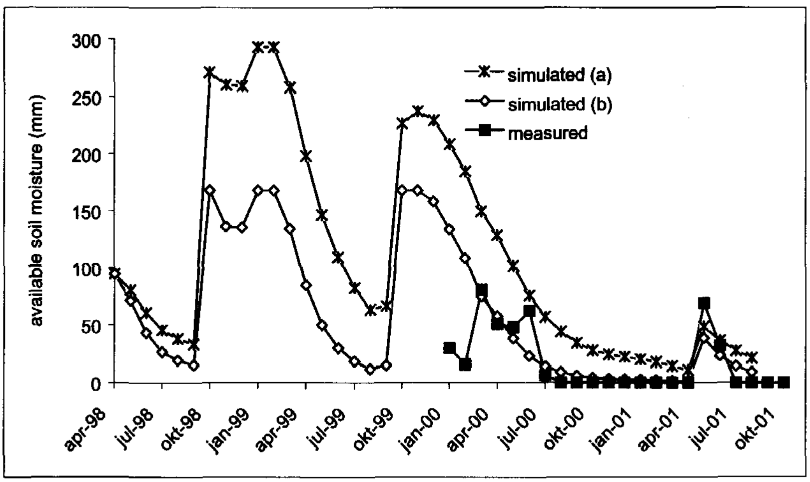

Figure 8.3 *Simulated and measured available soil moisture at the terrace of Amrich jessr; (a) and (b) represent simulations with a maximum ASW of 293 and 168 mm respectively.*

Assuming that available water over the remaining period (April 1998 – December 1999) is adequately simulated, olive yields were calculated (Table 8.3). Simulated olive yields in the years 1999-2001 were very low. The important decline in available soil moisture by the end of each summer (August) (Figure 8.3) is responsible for this fact. Maximum ASW does not seem to represent an important factor in the determination of the yield, because no important rainfall events were registered at the end of spring in the years considered. Although both simulations predicted some olive production, in reality no olives were harvested in either of the years 1999-2001. One reason for this could be that olive quantity was too low in relation to labour costs of harvesting, a factor that may be overlooked by the methodology applied.

Table 8.2 *Estimated and measured olive yields in Chaal, Sfax region (reference yield 176 kg tree^{-1}).*

Year:	*1988*	*1989*	*1990*	*1991*	*1992*
Estimated yield (kg/tree)	13	17	97	10	87
Measured yield (kg/tree)	0	22	115	0	73

Table 8.3 *Estimated and measured olive yields at Amrich jessr (reference yield 100 kg tree^{-1}).*

Year:	*1998*	*1999*	*2000*	*2001*
Estimated yield[1] (kg tree^{-1})	29	9	12	2
Estimated yield[2] (kg tree^{-1})	28	4	4	1
Measured yield (kg tree^{-1})	n.a.	0	0	0

Note 1: based on a maximum ASW of 293 mm.
Note 2: based on a maximum ASW of 168 mm.

8.3.2 Economic evaluation

Financial Cost-Benefit Analysis

Amrich jessr was constructed in 1965 and olive trees were planted on the terrace right after construction. Construction costs, in constant prices, were reconstructed by considering the volume of earth movement and daily wage rates (labour opportunity costs). As the dike is 3 m high, 5 m wide and 113 m long, its volume is around 1695 m^3. These are the dike's dimensions right from the start: a spillway is included to regulate the amount of water and sediments that can be harvested. The height of the spillway is adjusted a few times during the economic life of the WHT unit. An estimated 170 man-days are necessary to undertake jessr construction, at a daily cost of TD 3.50. Olive tree planting constituted an additional investment of TD 49, including digging of plantholes, purchasing tree saplings, watering, manure and labour costs. The total investment is therefore estimated at TD 642. If the first two years are dry, replanting is necessary at an estimated cost of TD 40. Maintenance costs of the jessr unit consist of an average 5.1 man-days y^{-1} and include allowances for repairs of the dike and adjusting spillway height. Production costs have been assumed to be governed by farmers' perception of the conditions for production, in terms of a dry, average or wet year, except for grazing, for which a fixed labour opportunity cost was set at 2 man days ha^{-1} y^{-1}. For cereals, labour investment amounts to 5, 15 and 18 man-days ha^{-1} y^{-1} for the three types of years distinguished. For olive labour requirements see Table 8.4.

Benefits of jessr construction are principally formed by intensified land use. In the without case, the total area occupied by impluvium and terrace is assumed to be used for extensive grazing and has a productivity of 50, 100 and 200 *Unités Fourragères* (Fodder units) per hectare respectively for a dry, average and wet year. Fodder units are valued at TD 0.20. In the case of jessr construction, the impluvium can still be used for grazing, and on the terrace area cereals and olives are produced. Up to year 6 after construction, cereals are planted on the whole terrace, thereafter only on one half. Cereal yields are rated rather high at 400, 800 and 1200 kg ha^{-1} respectively for a dry, average and wet year, due to the amendment of nutrients from the impluvium. In reality, cereals are only cultivated in years with sufficient autumn precipitation. Reference olive production is related to tree age as shown in Table 8.4. Potential olive production is derived from the reference production by considering 'on' and 'off' years, making use of the yield consistency index. Actual production is finally calculated using parameters defining yield reduction as a function of rainfall characteristics as follows: in a dry year, fruiting and vegetative yield reduction are respectively 40% and 14% and in an average year 20% and 5%. In a wet year, no yield reduction occurs and no initial vegetative yield reduction is taken into account for the first productive year. Wheat and olive prices are TD 0.40 and TD 0.28 per kg respectively (1997 prices).

Table 8.4 *Olive labour requirements and reference yields as a function of tree age and type of year.*

Years after planting	*Dry year*	*Average year*	*Wet year*	*Reference yield*[1]
		man-days year^{-1}		*kg olive tree*$^{-1}$
1-5	10[2]	5	5	0
6-7	5	6	7	20..25
8-10	5	7	7	30..40
11-16	6	7	8	50..75
17-20	7	9	10	80..95
21-30	8	10	12	100

Note 1: Estimated at yearly increases of 5 kg, adapted to the method here proposed from CNEA (1996);
Note 2: In dry years, initially more labour is required for watering the olive trees.

Figure 8.4 shows historical rainfall data of Beni Khédache (1969-2000). Based on relative divergence from the mean annual precipitation (235 mm), years were classified as average if within the range mean ± 20% and otherwise as dry or wet. Apart from the number of dry (13), average (10) and wet (7) years that can be expected during the evaluation period of 30 years, these historical data were also analysed for the probability of different sequences: 64% of dry years are followed by an average one, and 18% each by another dry year or a wet one. Average years are followed by wet ones (50%), dry ones (40%) or another average one (10%). Wet years are almost always followed by dry ones (83%), sometimes by an average one (17%) and never by another wet one. Figure 8.5 shows cash flows for the most favourable and most unfavourable sequence of years that can be expected based on these analyses. In both cases the financial result is negative (NPV of TD –621 and TD –622 respectively) and the IRR well below the social discount rate (2.2% and 1.3% respectively). Thus, investment in jessr construction is unattractive to individual farmers if no form of subsidies or other incentives are given.

Economic Cost-Benefit Analysis

Societal benefits of WHT are not confined to on-site effects. However, on the scale of a single WHT it is hard to value off-site effects. When considering on-site effects only, the economic CBA of Amrich jessr gives only slightly better results than the financial analysis. The cost of construction is considerably cheaper, because daily labour opportunity costs are valued considerably lower at TD 2. Benefits are slightly lower because the economic accounting price of wheat is somewhat lower (TD 0.26 per kg in 1997). This still shows that on-site effects alone cannot justify investment in construction of WHT (see also Sghaier *et al.*, Chapter 9).

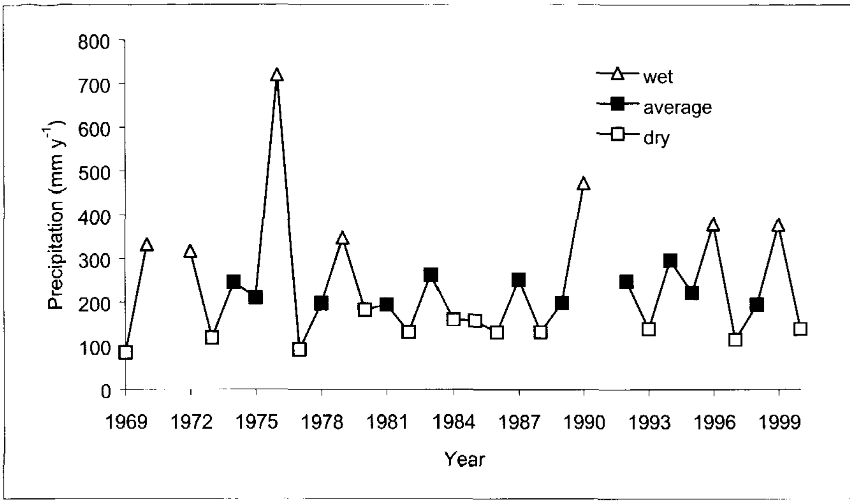

Figure 8.4 *Historical annual rainfall data recorded at Beni Khédache showing sequence of wet, average and dry years.*

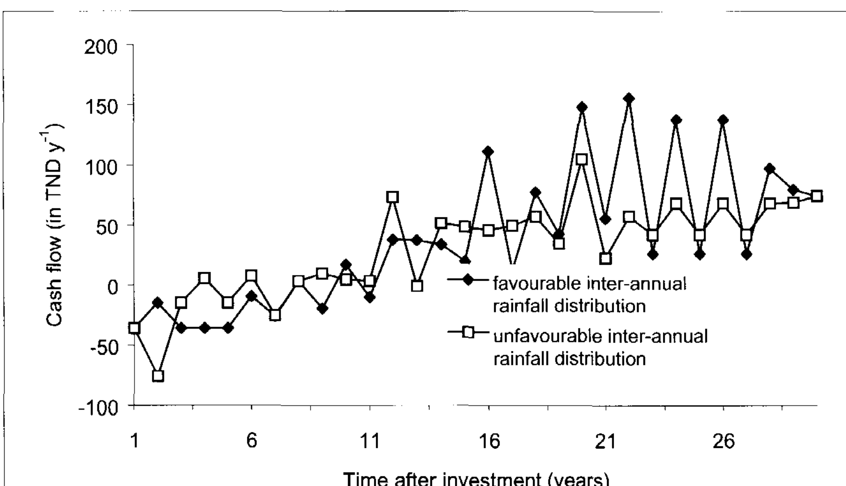

Figure 8.5 *Cash flows for financial CBA of jessr construction for two rainfall scenarios: the most favourable and the most unfavourable sequence of years.*

8.4 Discussion

The impact assessment methodology presented could not be thoroughly tested. However, it does not require many input data and can give an idea of the effect of WHT on crop (olive) yield through simulation of the water balance and available soil moisture. Critical factors in the model are maximum ASW (see below) and the values of crop and yield response factors and the yield consistency index. For calibration of the model one would need to effectuate rainfall amount and intensity measurements on the exact site and long-term experiments to arrive at good estimates for the intrinsic model factors (kc, ky and YCI).

Although none of the years considered has been very favourable, either due to overall lack of rainfall or due to its unfavourable distribution over the year, the jessr WHT was shown to raise the quantity of available water at the terrace area (from 302 mm to 586 mm in the hydrological year 1998/1999, from 145 mm to 431 mm in 1999/2000 and from 10 to 131 mm in 2000/2001). Rainfall intensity is a much more important factor to predict the occurrence of overland flow (and consequently run-on on the terrace area of a jessr) than rainfall amount. The occurrence of water supply (rainfall + run-on) in spring is a determining factor for the degree of yield reduction during the hot and dry summer months. In the years 1999-2001 total precipitation in spring amounted to 30, 33 and 6 mm respectively, all well below the average (68 mm) and median (46 mm) values obtained from statistical analyses of the rain gauge Beni Khédache (1969-2000) (Tanghe, 2002). Table 8.5 shows the effect different amounts of additional water supply in May would have had on olive yield. Small amounts of rainfall (e.g. 10 mm) with high intensity may cause these amounts of supply. The effect on yield much depends on maximum ASW and obviously, if this capacity is lower (e.g. 168 mm instead of 293 mm, see Section 9.3.1) yields will benefit less: under the cumulative effect of an additional water supply of 200 mm, for example, yields may rise to 37, 16, 22 and 5 kg $tree^{-1}$ respectively for the years 1998-2001 which is well below the values presented in Table 8.5.

The effect of maximum ASW (a function of rooting depth and soil type) was also demonstrated in Figure 8.3. An important aspect of jessr construction in this respect could be the build-up of a deep, medium-textured soil behind the dike. Snane and Mechergui (1996) report on a study of annual sediment deposits of 4.2 – 19.5 cm. Heirman (2002), based on the model of Biesemans (2000), arrives at a maximum of 1.4 cm of sediment for a single rain shower. However, the next most eroding rain shower in the period April 1998 – August 2001 only resulted in a sediment layer of 0.3 cm, casting doubt on the results of Snane and Mechergui.

In any case, the amount of water and sediment retained on the jessr terrace depends on the height of the spillway, a critical factor in jessr design. If it is too high, under influence of accumulated water on the terrace this may lead to instability and collapse of the dike, causing a chain-reaction of breakdown of downstream located jessour. This occurred in March 1979, when 50% of all jessour in the Matmata Mountains were destroyed (Snane and Mechergui, 1996). If it is too low, insufficient water can be accumulated on the terrace and trees and crops cultivated will always suffer moisture stress.

Another important design factor is the Catchment area to Cropped area Ratio (CCR). In the case of Amrich jessr, the CCR is 29. According to Tanghe (2002) a CCR of 18 would be sufficient for olive cultivation at Amrich, based on average annual precipitation. The present study does not support this view because distribution of rainfall over the year is unpredictable. Snane and Mechergui (1996) found an optimal value of CCR of 150, while actual values were found to be around 20. However, as Qureshi and Willardson (1994) showed for a completely different WHT in Pakistan, reaching maximum production on a small cropped area while sacrificing the remainder of the land as impluvium may not compensate for the loss of potential cropping area incurred, even when considering that production per area unit on an extended cropped area would be lower.

With regard to the economic evaluation, a critical point was identified in the increase of production of 6-12 year-old trees. The effect of WHT on the diminution of the length of the unproductive period has large consequences for economic viability. Also, reference yield of olive trees grown on jessour might be higher than the overall average; e.g. Snane and Mechergui (1996) talk about olive production of 200-300 kg $tree^{-1}$ on jessour as opposed to only 30 kg $tree^{-1}$ under normal (arid) field conditions.

In an evaluation of olive production in a low rainfall area (annual precipitation 191 mm) in Jordan, Al-Kadi (1997) concludes that while supplementary irrigation is definitely necessary during summer, individual construction of WHT maybe prohibitively expensive.

Although the on-site impact of WHT might not justify investment, governments should seriously consider off-site benefits as well, as is shown by Sghaier *et al.* and De Graaff *et al.* (Chapters 9 and 11). WHT play a role in flood control, diminution of erosion, groundwater recharge and improvement of life quality in relatively disadvantaged rural areas, possibly halting migration.

Table 8.5 *Simulated effect of additional water supply on olive yield (kg tree^{-1}Amrich terrace.*

Year:	*1998*	*1999*	*2000*	*2001*
Standard simulated yield	29	9	12	2
Effect of single additional water supply of 50 mm in May	30	11	15	4
Effect of single additional water supply of 100 mm in May	34	13	19	5
Effect of single additional water supply of 200 mm in May	43	19	31	5
Cumulative effect of additional water supply of 200 mm in each May	43	26	42	9

8.5 Conclusion

A relatively simple method is presented to assess the on-site impact of WHT, with special reference to the jessr technique, which is widely applied in the Matmata Mountains in southern Tunisia. On the terrace area of jessour, arboriculture can be practised in areas otherwise not suitable. This can be attributed to the run-on of overland flow on the terrace area, where it contributes to available soil moisture and plant nutrients. Moreover, behind the dike of such techniques sediments accumulate which help increase the water storage capacity. Despite of limited possibilities to calibrate the developed model, it is concluded that it presents a useful tool in the financial evaluation of WHT. Cost-Benefit Analysis of the jessr technique shows that on-site effects alone do not justify investment in WHT. The need to take into account off-site effects is stressed.

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9 ECONOMIC ASSESSMENT OF SOIL AND WATER CONSERVATION WORKS: CASE OF THE OUED OUM ZESSAR WATERSHED

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Abstract

This article presents the results of the extended cost-benefit analysis whereby the economic assessment is enlarged with environmental phenomena such as water erosion and groundwater recharge. This work represents a contribution to the ex post assessment of the national strategy for soil and water conservation (1990-2000) undertaken in one of the most important watersheds in the arid regions of Tunisia: the watershed of Oued Oum Zessar.

The applied methodology is an interdisciplinary approach based on the application of the FORCES-MOD model, intended for extended cost benefit analysis (ECBA) and conceived by the World Bank and the FAO for the Tunisian context. The results obtained revealed that profitability criteria improved significantly as a function of integrating positive environmental and social impacts.

Keywords: extended cost-benefit analysis, ex post assessment, FORCES-MOD model, soil and water conservation, arid watershed, Tunisia.

9.1 Introduction

During the last decade, the Tunisian government implemented the national strategy for soil and water conservation (1990-2000). This strategy mobilised important funds at the national and regional level. Different actors (decision-makers, developers and researchers, etc.) have felt the need to proceed with a technical and socio-economic impact assessment of this strategy. However, while the classical economic impact assessment of projects is easy to carry out, difficulties still persist for the economic assessment of environmental phenomena related to soil and water conservation. In addition, the risks induced by the climatic variability in the arid and semi-arid zones represent also a very important aspect in the analysis.

In this framework, the objective of this article consists of carrying out an extended economic assessment of the SWC strategy, undertaken in the watershed of Oued Oum Zessar (south-eastern Tunisia) between 1990 and 2000. This extended cost-benefit analysis (ECBA) could be realised thanks to the application of the FORCES-MOD model (FAO & World Bank, 1994). This research has been undertaken by an interdisciplinary team associating soil science specialists (hydrology, hydro-geology and SWC) with agronomists and economists.

9.2 Extended Cost-Benefit Analysis with the FORCES-MOD Model

The extended cost-benefit analysis was carried out by applying the FORCES-MOD model in order to assess the costs and benefits of SWC works undertaken between 1990 and 2000 in the research watershed. It is an ex post analysis for the effective investments carried out for the strategy during the period 1990-2000, with future benefits estimated for the period 2001-2019. So, the global horizon of the CBA is thirty years, a period judged sufficient to take into account the majority of costs and benefits of investments and to allow the depreciation of the works implemented. Thanks to the FORCES-MOD model external environmental phenomena and tangible as well as intangible effects could be integrated in the analysis. Developed initially by the World Bank and FAO to apply CBA for forestry and SWC (FORCES-MOD) projects, the FORCES-MOD model permits to undertake CBA for projects with important environmental and social impacts. The CBA is undertaken in five steps as described in figure 1 (Mahdhi and Sghaier, 2000). The extended analysis is divided in two parts. One concerning the off-site effects related to the activities, such as the reduced sedimentation in reservoirs and reduced flood damages downstream, and the other focussing on the indirect and intangibles effects, such as effects on the groundwater table, on quality of life of the population, etc.

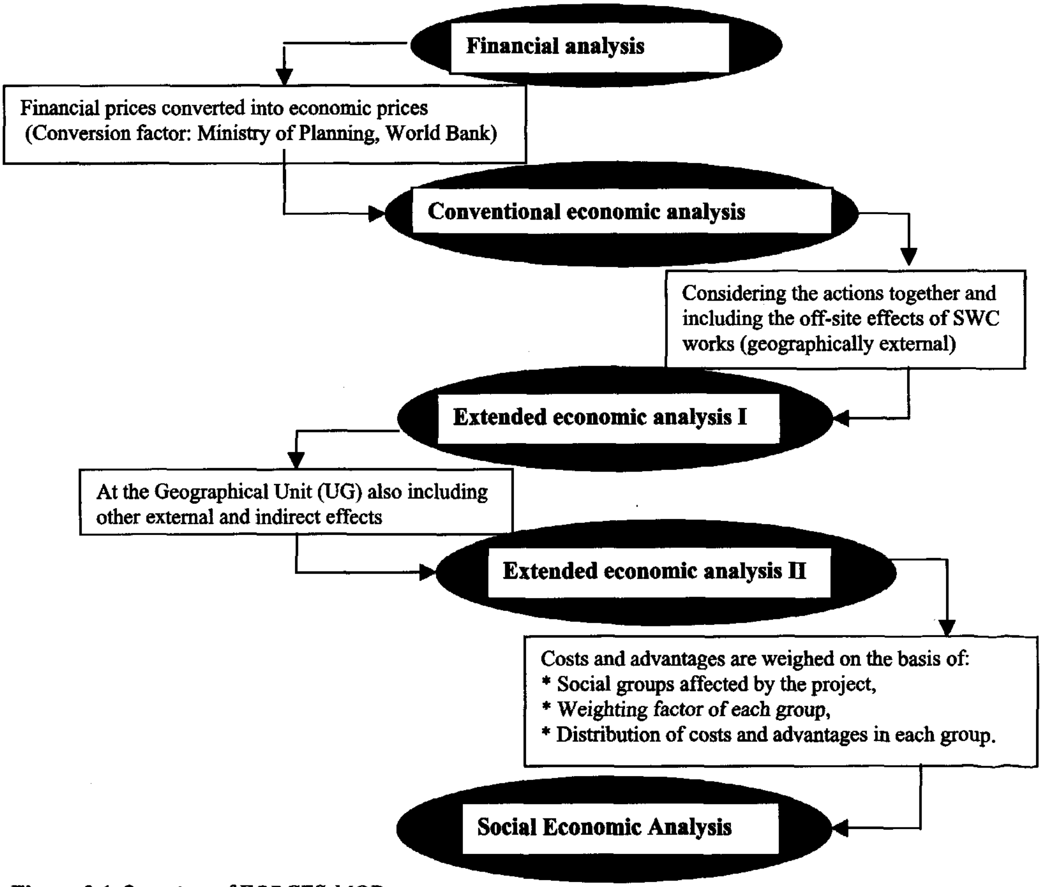

Figure 9.1 *Overview of FORCES-MOD components*

The technical, physical and economic data concerning these works were collected from socio-economic surveys, from archives of the technical services of SWC and crop production in Médenine, bibliographical sources and by consulting resource persons at local and regional level. Socio-economic surveys have been carried out with a stratified representative sample of 120 farmers (8% of total farmer population), distributed spatially (upstream and downstream) and in a homogeneous manner in the watershed. Three main actor groups were identified: beneficiaries of SWC works, livestock breeders and irrigation farmers (Table 9.1).

Table 9.1 *Survey sample by actor group and by area.*

Actor group: *Area:*	*SWC – Beneficiaries*	*Livestock breeders*	*Irrigation farmers*	*Total*
Upstream	35	6	4	45
Piedmonts	19	6	5	30
Downstream	13	16	16	45
Total	67	28	25	120

These different survey activities made it possible to make an inventory of the works undertaken within the framework of the national SWC strategy, to analyse the various production systems in the research area, and to evaluate the costs and benefits of SWC works, including the fruit tree production. In addition, following the analysis of rainfall data of Koutine and Béni Kdache stations, over a period of thirty years, the rainfall years were split up into three classes: dry, normal and humid. This classification has been used subsequently to integrate climatic risk and to adjust the yields, charges, incomes and costs of repair at the level of the extended economic analysis.

9.3 Research area: watershed of Oued Oum Zessar

The watershed of Oued Oum Zessar is located in south-east Tunisia (North West of the city of Médenine). Administratively, it belongs to three 'delegations' or districts (Médenine Nord, Sidi Maklouf and Béni Khédache) of the province of Médenine. It covers an area of 33,600 ha and stretches from the upstream area of Béni Khédache to the downstream area of sebkhat Oum Zessar. The population is estimated, according to the census of 1994, at 24,188 inhabitants. It is considered one of the most important hydrological watersheds of the region with an average annual runoff of 4.7 millions m^3 (Derouiche, 1997). See chapter 2 for more details.

9.4 Inventory of SWC works and production systems

9.4.1 *Inventory of SWC works*

The works undertaken in the framework of the SWC strategy in the watershed for the period 1990-2000 were as follows:

Establishment of SWC works
This concerned the works related to the construction of jessours (657 ha), tabias (5,725 ha) and contour stone ridges (1,014 ha) totalling 7,406 ha (Figure 9.2).

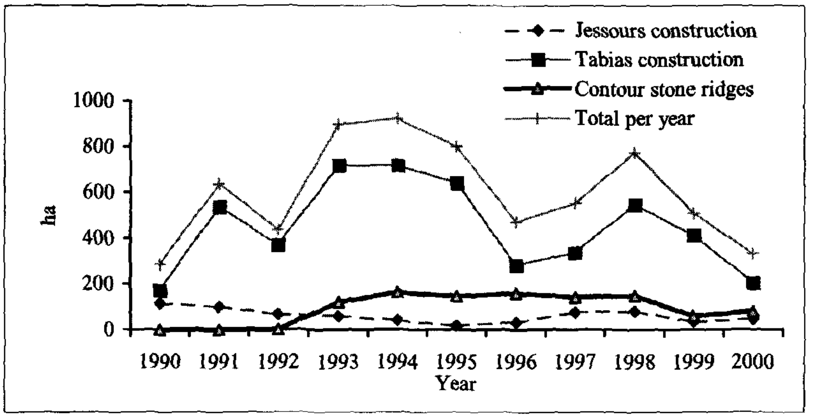

Figure 9.2 *Evolution of the undertaken SWC works in the study area (1990-2000).*

As shown in figure 9.2, the rhythm of realisation is variable. Two high-speed implementation periods could be distinguished: 1990-1994 and 1997-1998. After 1998, the rhythm slowed down because of the gradual termination of the programme.

Maintenance, safeguard and consolidation of SWC works
This concerned the maintenance of jessours, of other works (tabia, and contour stone ridges) and of pastoral plantations. Furthermore this concerned the maintenance of fruit tree plantations behind these structures and the maintenance of other pastoral plantations on an area of 3688 ha. It represents 50% of the total treated area but only 11% of the total watershed. The fruit tree plantations (1,729 ha) and the maintenance of structures (2,815 ha) represent the two main activities in the research area.

Surface water mobilisation
Two types of gabion structures have been installed on the wadi beds (Boufelgha, 1995): recharge units and flood spreading units. A total of 177 groundwater recharge units and 21 flood spreading units have been established.

9.4.2 *Production systems*

The production systems in the study watershed are diverse and differ considerably between upstream and downstream areas. They are characterised mainly by:

- an irregular rainfed agricultural production that varies from one year to another according to the rainfall regime;
- the development of fruit tree plantations (90% olive) and annual cropping (episodic cereals) after removal of the natural vegetation on pasture lands;
- *the development of irrigation systems based on shallow and deep aquifers;*
- the accelerated transformation of livestock systems towards more intensive (partly zero-grazing) systems that depend less on natural grazing pastures;
- The extent to which traditional or modern soil and water conservation techniques are applied.

On the basis of the above main features of production, the following five production systems can be distinguished:

a) *The rainfed annual crops.* In spite of the additional received runoff water, the rainfed annual crops are only cultivated once in two or even three years (Labrass, 1995). The main crops are cereals (wheat and barley) and legumes (faba bean, lentil, green pea) mainly used for family consumption.

b) *The (olive) tree production system.* This system consists of rainfed tree cropping ('arboriculture'), dominated by olive trees. It is mainly encountered in the plain and in the piedmonts. The farm size varies from 5 to 46 ha. Other tree species are also present such as almond, apple, etc.

c) *Irrigated agricultural systems.* Two sub-systems can be distinguished: the sub-system of private irrigated farms is based on surface wells. It is localised in the upstream area (at Ksar Hallouf) and in the downstream area as well but of less importance. The agricultural production is based on cash crops, greenhouses, vegetables and fruit trees. The subsystem of public irrigation schemes or 'perimeters' is based on collective tube-wells, normally established by the State. The water management is ensured by a water user association known as the 'AIC'. These 'perimeters' are situated in the downstream zone of the watershed, such as the Kosba irrigation scheme.

d) *The mixed crop-livestock production system.* This system is influenced by the climatic irregularities. The agriculture is of the rainfed type, associated with an important livestock husbandry component. Two sub-systems can be identified. Its small area and the large extent of income from non-agricultural sources mark the sub-system of the marginal agriculture. The livestock sub-system consists of livestock breeders and herdsmen, who are transforming their system by introducing a cropping component which importance gradually exceeds that of the livestock husbandry. It is mainly found in the downstream area of the watershed.

e) *The rainfed agricultural systems behind SWC structure.* Developed essentially in the upstream areas, these systems are based on various runoff water harvesting systems, as discussed in this book. The thousands years old technique of Jessour is mainly found in the mountainous zone of Beni Khédache. These systems are marked by fruit tree development, notably olives. Annual crops such as cereals, legumes and vegetables are also occasionally practised. On the terraces of SWC structures (jessour, tabias, dry stone ridges), the fruit trees are arranged in inter-rows with the three main species encountered in the region. Generally, olive trees are planted, with in between rows of almonds and/or fig trees. The planted area has increased from about 490 ha before the start of the SWC strategy to 2,285 ha in 2000. The tree plantations behind tabias recorded the highest growth rate. The fruit tree density and the area cropped differ according to the type of SWC structure.

   For jessours, the trees are planted at 4 to 5 m upstream of the dike with an average density of 62 trees ha^{-1}, mainly olive trees, mixed with fig or almond trees. The average parcel size is 0.7 ha by jessour.

   In tabias, inter-row plantations are frequently encountered. The main species are olive and almond trees (25 trees ha^{-1}). The average parcel size is 0.9 ha.

Along contour stone ridges, inter-row tree plantation are also mainly based on olives, figs and almond trees (8 trees ha^{-1}). These structures occupy the sloping areas (slope more than 10%) on the hills. The average parcel size is 0.6 ha.

9.5 Costs and benefits of SWC works in Oum Zessar watershed

9.5.1 The costs of the SWC-works

The global investment in SWC was 9.86 MTD. It concerned the watershed SWC treatments (4.9 MTD), the maintenance, safeguard and consolidation of SWC works (2.14 MTD) and the surface water mobilisation (2.81 MTD). The evolution of annual investment by component is shown in figure 9.3.

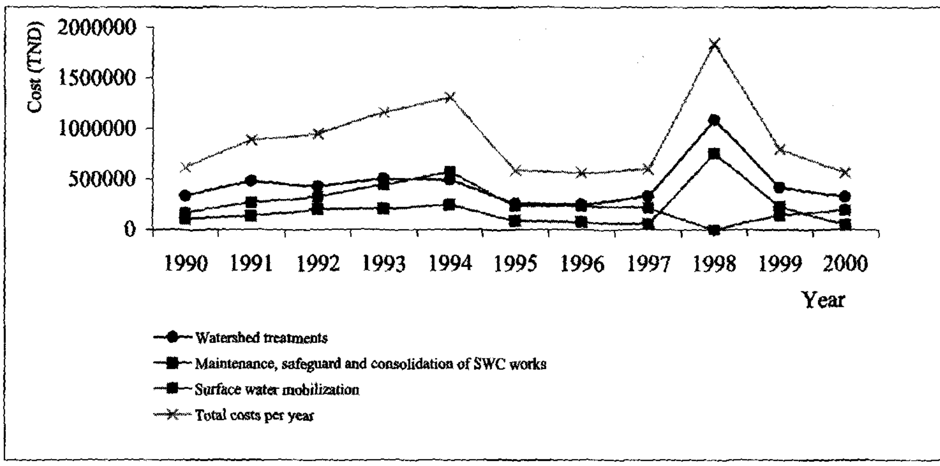

Figure 9.3 *Evolution of investment costs by component from 1990-2000.*

The annual costs of maintaining the surface water mobilisation works were estimated on the basis of norms established by FAO and CNEA (Table 9.2). For the other works (jessours, tabias, etc.), these costs were determined by analysing the available archives at the SWC service in Médenine.

Table 9.2: *Maintenance rate and lifespan of gabion units.*

	Maintenance rate	*Lifespan*
Recharge unit	5%	30
Spreading unit	5%	30

Source: CNEA (1998).

Exploitation expenses include mainly the costs related to mechanical and animal traction, hired labour and supplementary irrigation. These costs are variable and depend on the rainfall pattern (dry, normal or humid year), the crop species, trees age and structure type. Over the period concerned (30 years), the annual exploitation expenses vary from 0 to 192 DT ha^{-1} in the case of jessour and contour stone ridges and from 20 to 210 DT ha^{-1} in the case of tabias.

9.5.2 The benefits of the SWC works

The benefits of SWC works consist of several beneficial effects of which the most important are:

- the increased plant and vegetative cover with all its direct and indirect effects;
- the extension of fruit tree plantations and cereal cropping in the areas treated by SWC works;
- the contribution to the recharge of groundwater aquifers through the gabion structures installed on the wadis;
- the improvement of the quality of life of the population;
- The reduction of income gaps between upstream and downstream groups within the watershed.

Benefits of SWC works in the research area have been observed at three levels: the farm (production increase, etc), the community (improvement of quality of life, etc.), and the environment (groundwater, ecosystem, etc.). These benefits are assessed subsequently through a Financial Analysis (FA), a conventional economic analysis (AEC), the two types of Extended Economic Analysis (EEA1) and (EEA2) and a Social Economic Analysis (SEA). At each step of the FORCES-MOD model, the benefits have been estimated on the basis of the following data and hypotheses:

Estimated tree crop yields

The impact of SWC works on fruit tree production took into account tree age, the annual rainfall class (climatic variability) and the type of structure. This evaluation was undertaken on the basis of field survey data and some previous research by IRA, CNEA (*Centre National des Etudes Agricoles*) and IO (*Institut d'Olivier*). Olive yields were estimated according to the results obtained by Lakhoua (1982, cited by Ennabli (1993)) who found that the yield of year N is correlated to the annual rainfall of the year N-1 as follows:

$Y = 0.2962 + 0.1441\,X$, for the Meskat system (Central Tunisia)

$Y = 0.1387 + 0.1515\,X$, for the Chemleli variety in the region Sfax (Southern Tunisia)

Where:

Y = Yield (kg $tree^{-1}$)

X= annual rainfall of the previous year (N-1)

For the new plantations, the annual yield has been based on the survey results and previous research by IRA (1998) and CNEA (1996).

Gross production value by type of exploitation

The agricultural production value depends on the climatic variability and the type of structure. It is relatively low and does not exceed the average of 252 DT ha^{-1} and 78 DT ha^{-1} after and before the implementation of the SWC strategy. The jessour-based farms recorded the highest (515 DT ha^{-1} benefit area) while the contour stone ridges generated the lowest production value (52 DT ha^{-1}) (Table 9.3).

Table 9.3. *Average agricultural production value per ha (DTN) by structure.*

	Jessours	*Tabias*	*Dry stone ridges*	*Average*
Before strategy	182	26	27	78
After strategy	515	173	68	252

Source: Our calculations.

When calculating the agricultural gross production value, the climatic variability, plantation date and probability of appearance of different types of rainfall years (dry, normal and humid) were taken into account. The results are reported in figures 9.4 and 9.5.

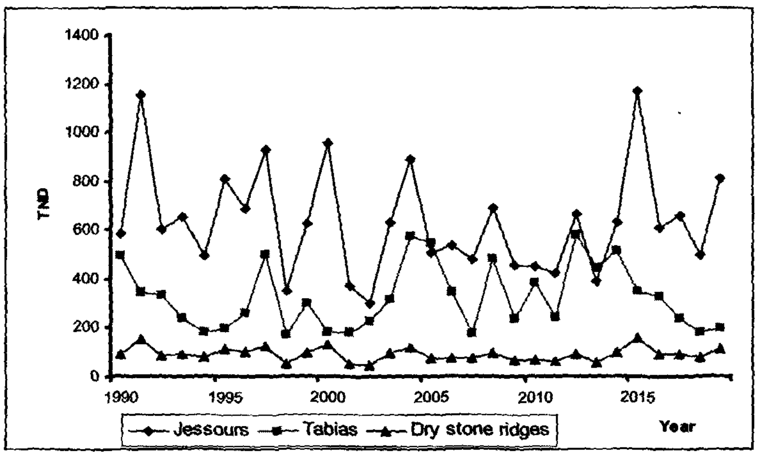

Figure 9.4 *Gross production value (DT) per hectare by type of structure and by year (case of already established plantations).*

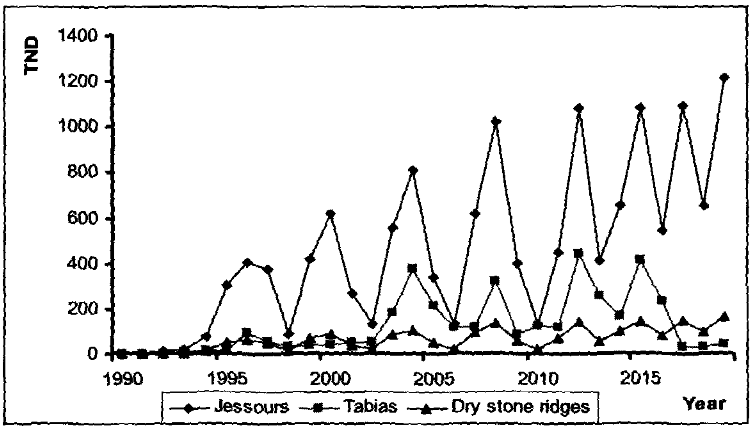

Figure 9.5 *Gross production value per hectare, by type of structure and by year (case of newly installed plantations).*

Figures 9.4 and 9.5 also show that the jessours performed best while the contour stone ridges recorded the lowest gross agricultural production value.

9.6 Application of the FORCES-MOD model

The application of the FORCES-MOD model enabled the calculation of the economic efficiency criteria: the internal rate of return (IRR) and the net present value (NPV) for the five analysis steps (financial analysis, conventional economic analysis, extended economic analysis 1, extended economic analysis 2, and social economic analysis). The general hypotheses of the CBA are:

- the discount rate retained for the cost benefit analysis corresponds to the official 1997 rate published by the Central Bank of Tunisia (10.8%);
- for the CBA a period of thirty years is considered, which is sufficient to cover the technical and economic lifetime of the SWC works and the great majority of the benefits;
- the prices used in the financial analysis correspond to the average market prices in Médenine over the period 1995-2000;
- the agricultural benefits only consist of the tree crop production. The annual crop production has not been taken in account;
- The SWC works are subdivided into seven components (jessours, tabias, contour stone ridges, animal feed plantations, and recharge and spreading gabion units);
- The establishment of jessours, contour stone ridges and pastoral plantations is supposed to be made on grazing land (without-case) of which the production value per hectare is respectively 50 UF[1], 100 UF and 200 UF in dry, average and humid years;
- The establishment of tabias is supposed to be made on cereal land (without-case) having a production cost per ha of 10 TD and a yield per hectare depending on the average annual rainfall;
- The annual development of farm expenses and gross production value depends on the annual rainfall pattern and the sequence of different types of rainfall years over the period considered (30 years).

The results for the different steps of the application of the FORCES-MOD model are as follows:

9.6.1 Financial analysis

In this analysis market prices are applied for all costs and benefits taken into consideration. Costs and returns are calculated respectively for each component with and without its implementation over the period of 30 years. As shown in figure 9.6, the difference between the benefits generated by the strategy and the total costs (investment, maintenance and exploitation) remains negative during the first eleven years and shows important fluctuations due to rainfall variations.

This financial analysis therefore shows a low Internal Rate of Return (IRR) of 5.5% and a negative Net Present Value (NPV) of -1.065 Million TD (MTD). On the financial side, these results are not surprising because of the heavy investments, the retarded benefits of tree crops and the adverse climatic conditions and fluctuations.

[1] UF : *unité fourragère* = equal to the animal feed value of 1 kg barley

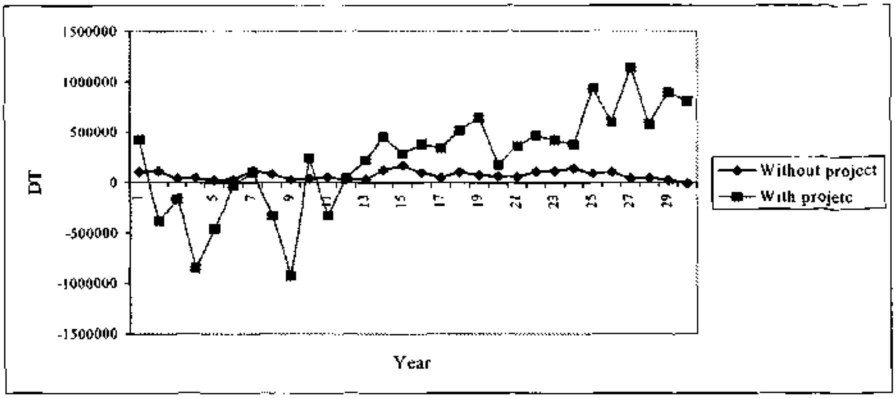

Figure 9.6 *Costs and benefits with and without SWC works, over 30 year period (1990- 2020)*

9.6.2 Conventional economic analysis (CEA)

At this stage, the financial prices (market prices) of costs and benefits are transformed into economic prices while reducing market distortions (subsidies, transfer payments, taxes, etc.). This transformation is performed by using conversion factors adapted to the Tunisian context (World Bank, 1994). For wages of unskilled labour this conversion factor is for example 0.6, considering the importance of job creation for this group with a rather high underemployment. When moving from the financial analysis to the economic analysis, the project becomes more interesting at the community level with a NPV of 0.285 MDT and an IRR of 13%, which is a clear improvement compared to the financial analysis. When market distortions are reduced, the SWC strategy will have a higher economic impact.

9.6.3 Extended Economic Analysis 1 (EEA)

At the level of EEA1 only one type of external or off-site benefits has been considered and this is related to the failure of structure by flooding. The underlying hypothesis is that SWC works permit to reduce the probability of structure failure. It has been estimated that the costs of repair can be reduced by 415 DT ha^{-1} for jessours and 109 DT ha^{-1} for tabias for the year 2000. It is evident that the probability of structure failure is highly related to the rainfall intensity. It has been assume that SWC works would reduce the probability of failure (and thus the costs of repair) according to the percentages in Table 9.4.

Table 9.4 *The probability of structure damages (before and after strategy)*

Daily rainfall intensity	*Jessours*		*Tabias*	
	Before	*After*	*Before*	*After*
30 mm day^{-1}	15%	-	-	-
30-60 mm day^{-1}	30%	5%	10%	-
60-80 mm day^{-1}	50%	15%	25%	5%
80-100 mm day^{-1}	70%	25%	50%	15%
100-150 mm day^{-1}	90%	50%	80%	40%

Sources: Sghaier and Chehbani (1997); A/CES de Médenine (2001, Pers. Com.).

While taking into account this fact, the IRR improves significantly to 18.4% whereas the NPV doubles to reach 0.80 MDT.

9.6.4 *Extended economic analysis 2 (EEA 2)*

At this stage, other external effects and intangible costs and benefits are considered. Two types of benefits have been considered:

- groundwater recharge, and
- the improvement of the quality of life

The assessment of the costs and economic benefits of the groundwater recharge is quite complex. Nevertheless, the additional annual infiltrated water volume infiltrated, following the installation of the recharge gabion units, is estimated to 480 000 m^3 $year^{-1}$ (Maati, 2001). This is used to irrigate an additional area of 40 ha (the average water requirement for the crops is 12,000 m^3 $year^{-1}$ ha^{-1}). The gross production value and exploitation costs are estimated to 700 DT $year^{-1}$ and 500 DT $year^{-1}$, respectively (Sow, 1999).

With regard to the quality of life of the local population within the watershed, the FORCES-MOD model assumes that this improvement could be expressed by a growth of per capita incomes of 5 TD $year^{-1}$. When taking into account these two benefits, the analysis shows a clear improvement of the IRR which now reaches 26% whereas the NPV exceeds 1 MDT (1.05 MDT).

9.6.5 Social economic analysis (SEA)

For the social cost benefit analysis, the population is subdivided into three groups according to criteria related to their production systems, their spatial distribution and degree of poverty, which is related to their location within the watershed.

- the first group consists of the population in the upstream part (with a weighing factor of 1.1),
- the second group consists of the population of the piedmont area (with a weighing factor of 1.15), and
- The third group consists of the population in the downstream part (with a weighing factor of 1.0).

The analysis revealed a minor further improvement of the results, with an IRR that reached 27.8% and a NPV that increased further to 1.15 MDT.

9.7 Results and discussion

Results

The financial IRR of the SWC investments is only 5.5 % whereas the conventional economic IRR is 13.3 %, or slightly higher than the social discount rate applied in Tunisia of 10.8 %. Taking into account the off-site or downstream effects related to the SWC works (extended economics analysis I) the economic profitability of the project becomes really attractive (IRR is 18.4 %). The integration of other external and intangible effects (extended economics analysis II) shows an additional increase of the IRR to 26.0 %. Finally the social economic analysis brings the overall internal rate of return to the level of 27.8 %.

Table 9.5 provides the results of a sensitivity test performed by using alternative discounting rates of 8 % and 13.8 % respectively. This test shows relatively large differences between the results for the different discount rates.

Table 9.5 *Summary of the CBA results as obtained with FORCES-MOD*

Discounting rate	*NPV in MDT*			*IRR (%)*
	8 %	*10.8 %*	*13.8 %*	
Financial analysis (AF)	-0.70	-1.06	-1.19	5.5
Conventional economic analysis (AEC)	0.93	0.28	-0.05	13.3
Extended I (AEE1)	1.68	0.80	0.13	18.4
Extended II (AEE2)	1.98	1.05	0.52	26.0
Social economic analysis (ASE)	2.17	1.15	0.58	27.8

Discussion

The extended CBA, performed by the application of the FORCES-MOD model, made it possible to take into account in the economic assessment such environmental phenomena as the destruction of structures by flooding, the recharge of groundwater and the improvement of the quality of life. The model also illustrates how the results of the extended CBA change at each of the different steps. It has been found that the economic efficiency criteria (IRR and NPV) jumped from a low value in the financial analysis to quite high values at the level of the extended economic analysis.

The economic analysis shows that the SWC works are profitable from a national economic point of view, with an IRR of 13.3 %. The inclusion in the analysis of the off-site or downstream benefits of reducing flood damage to structures (module EEA 1) improves the economic profitability considerably, with an NPV (at 10.8 % discount rate) of 0.79 MDT and an IRR of 18.4 %. And the incorporation of other external and indirect effects with no market prices (module EEA 2) such as the improvement of the quality of life and the groundwater recharge resulted in a further improvement with NPV of 1.05 MDT and IRR of 26.0. However, the assessment of benefits related to the improvement of the quality of life is based on assumptions that still need to be verified through specific detailed surveys. As a matter of fact, the application of extended cost-benefit analysis (FORCES-MOD) is highly dependent on the quality of the available information on natural resources. The final step in the assessment is social cost-benefit analysis, which show slightly higher efficiency indicators (NPV of 1.15 MDT and IRR of 27.8 %). The SWC works have apparently been slightly more beneficial for those of the three groups within the watershed (upstream, piedmont and downstream) that have fewer resources and are poorer.

The profitability of the SWC works is quite satisfactory in spite of the heavy investments and the still rather low agricultural yields after implementation. A sensitivity test indicates that the outcome shows some variation with different discount rates, but this does not influence the general conclusion that the SWC works are economically efficient, and in a particular when the external effects are incorporated in the analysis.

However, it is hard to identify and internalise all external effects in such analysis, and other positive and also negative effects could certainly occur. One could think of the many effects linked to erosion and sedimentation, to groundwater salinisation, to effects of increased use of pesticides and to forward and backward linkages and other multiplier effects.

However, the difficulties encountered in making a detailed assessment of such very complex environmental phenomena render their economic valuation more problematic, and will probably not have a major influence on the outcome.

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10 LA SEGUIA, UNE TECHNIQUE D'UTILISATION DE L'EAU: SON IMPACT SOCIO-ECONOMIQUE A TALKJOUNTE -MAROC

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Abstract

The WAHIA project, with its objectives to undertake an impact assessment and economic evaluation of different water harvesting techniques, has in Morocco selected as case study area the Talkjounte watershed on the southern slopes of the Haut Atlas and in the upper part of the Souss river basin.

The harvesting and utilisation of irrigation water in this watershed is mainly based on the distraction of water along the wadi. The analysis of costs and benefits has therefore been focused on two technical and social water use units: the seguia Tamazirt and the seguia Sins and secondly on the situation of the few wells that were recently introduced as irrigation technique in the region.

In terms of water harvesting techniques, water distribution systems and crop and agricultural production systems, the research results are very interesting.

Keywords: Costs, irrigation, production, seguia, social structure, Talkjounte.

10.1 La seguia, une technique handicapée par les héritages

L'écoulement permanent de l'oued Talkjounte à certains endroits sous forme de résurgences, appelées localement *ain* ou source, a donné lieu depuis plus de 2 siècles à des seguias dont les éléments techniques et d'organisation sociale de l'utilisation de l'eau sont examinés dans les précédentes présentations.

Nous soulignons ici que cette technique de collecte et d'utilisation de l'eau d'irrigation, qui a fait ses preuves un peu partout au Maroc sur les plans technique et organisationnel, rencontre ou présente tout de même un certain nombre d'entraves matérialisées dans le cas précis de Talkjounte à travers les inégalités d'accès aux ressources, les structures foncières paralysantes et l'incapacité de la technique de la seguia à réduire les déficits hydriques de plus en plus grands en raison, à la fois, des difficultés sociales d'accès à l'eau et de la faible portée de la technique de la seguia face aux sécheresses prolongées des dernières années.

10.1.1 L'inégal accès aux ressources : la terre et l'eau

Rappelons tout d'abord que dans le secteur étudié, le statut de l'eau est propriété privée (melk) indépendante de celle du sol. En d'autres termes, l'eau peut être vendue, louée, cédée, etc. à part, au même titre que la terre.

Le processus de distribution permet de livrer une part d'eau ou un temps d'écoulement à un individu qui en devient ainsi propriétaire, indépendamment de l'importance de sa propriété foncière. Ces parts d'eau sont proportionnelles, du moins à l'origine, à la contribution de chaque propriétaire dans les travaux de la construction ou du creusement de la seguia.

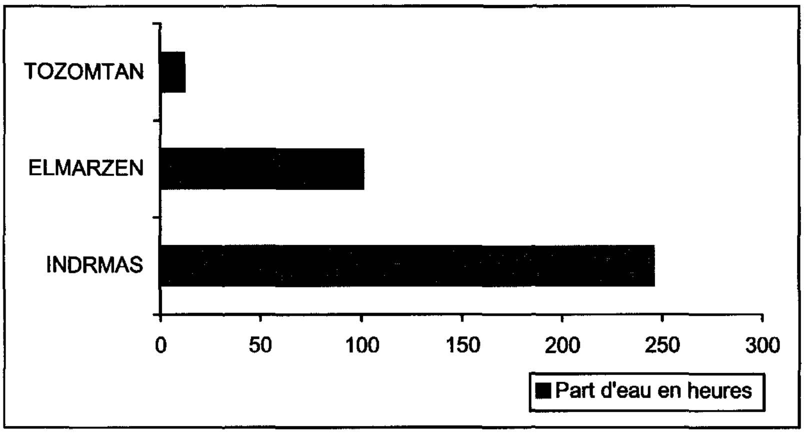

Figure 10.1. *La répartition inégale de l'eau entre les villages.*

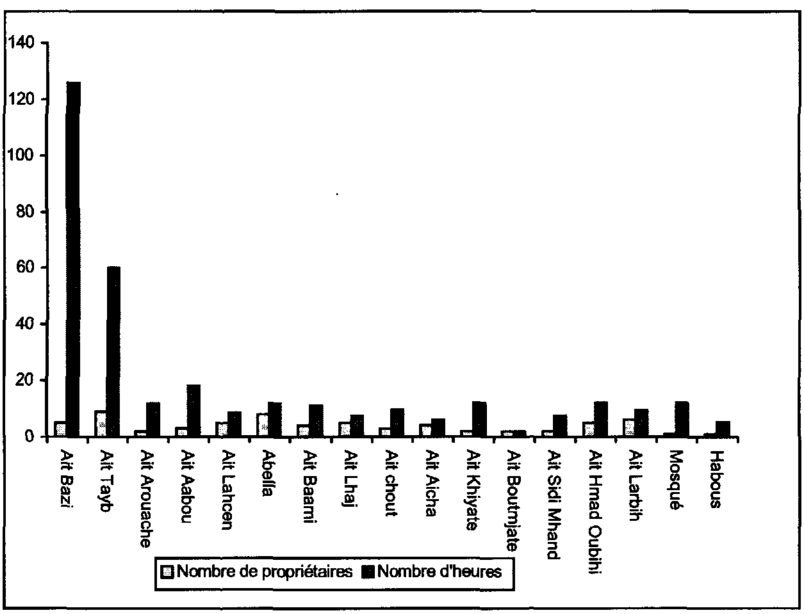

Figure 10.2. *La répartition inégale de l'eau entre les lignages.*

Comme il apparaît à travers les illustrations (Figures 10.1, 10.2 et 10.3), la répartition de l'eau, c'est à dire ce qui revient de droit à chaque catégorie de détenteurs : villages, lignages et foyers propriétaires est marquée par de très grandes inégalités.

Cette inégalité de la répartition de l'eau se retrouve dans la répartition des terres à tous les niveaux : villages, lignages, foyers et propriétaires.

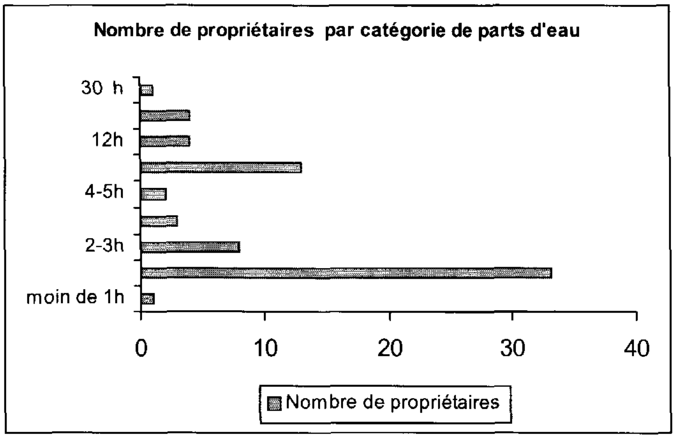

Figure 10.3. *La répartition inégale de l'eau entre les foyers propriétaires.*

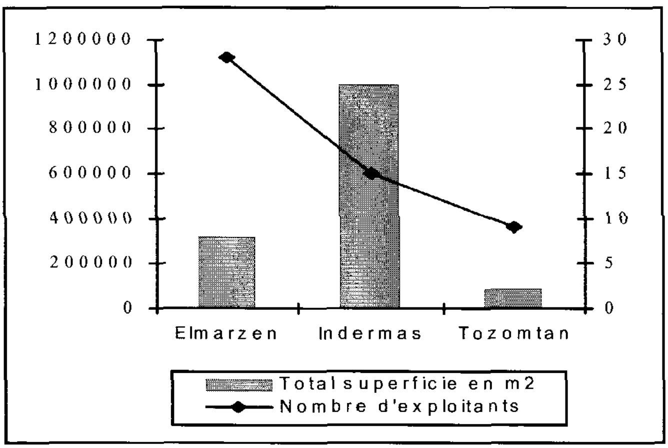

Figure 10.4. *La répartition inégale des terres entre les villages.*

Cette inégalité d'accès aux ressources : eau et terre, reflète en réalité la longue évolution historique et sociale de la région. Cette évolution est marquée en effet par d'incessantes rivalités entre villages, groupes sociaux et familles pour l'appropriation des différentes ressources. Dans ce sens, les ressources faisaient l'objet de compétitions au point où la main mise sur l'eau ou la terre était le fait d'un groupe social voire d'une famille à l'exclusion des autres. Et, compte tenu de la lente désagrégation des structures sociales héritées, l'inégalité d'accès aux ressources est encore visible à tous les niveaux.

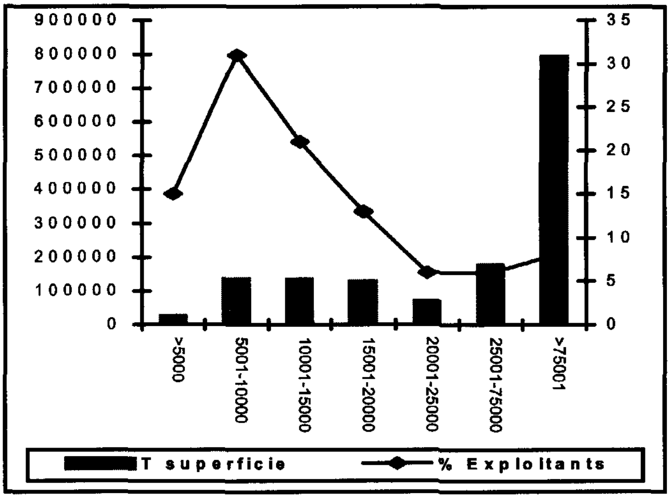

Figure 10.5. *Concentration de la propriété foncière.*

En considérant le niveau des exploitations, c'est à dire les foyers propriétaires, ces inégalités se traduisent par une concentration des terres et de l'eau aux mains de quelques foyers doublée d'une atomisation des terres et de parts d'eau restants parmi une majorité de foyers.

Ces répartitions inégales sont aggravées par l'exiguïté et par le morcellement des tenures se traduisant sur le plan des paysages agraires par une extrême densité du parcellaire et par la pulvérisation du domaine cultivable irrigué en une multitude de parcelles de quelques m^2.

Tableau 10.1 *Des propriétés foncières exiguës.*

Catégorie des parcelles	*Superficie (m^2)*	*% parcelles*
< 500 m^2	13500	12
1000-3000	243500	52
3001-6000	173000	21
6001-9000	24000	1
9001-15000	112000	4
15001-20000	32000	1
20001-30000	0	0
30001-40000	264000	3
>40000	540000	9

Tableau 10.2 *Des propriétés foncières morcelées.*

Nombre de parcelles	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
% exploitant	1,9	9,6	19	19	25	15	3,8	0	2

Comme illustré par les tableaux et graphique ci-dessus, la superficie des propriétés foncières est très réduite. En ne considérant que les parcelles, plus de 60% d'entre elles ne dépassent pas 0,3 ha. Cette exiguïté est doublée par le morcellement des propriétés s'éclatant en un nombre élevé de parcelles : plus de 25% des tenures se présentent en 5 parcelles dispersées et trop souvent éloignées les unes des autres pour former, en fin de compte, un ensemble cohérent et facilement exploitable.

10.1.2 La faible portée technique et organisationnelle de la seguia : insuffisance de l'eau

Le rapprochement, à titre indicatif, entre les débits disponibles dans la seguia (14,3 $l\ s^{-1}$ au mois de septembre 2000), les surfaces cultivables/irrigables et le cycle des parts d'eau, une fois tous les 16 jours, laisse voir d'énormes déficits dans le rapport. A l'échelle de l'ensemble du terroir irrigué, cet écart est très grand. Mais d'un propriétaire/exploitant à un autre l'écart est très variable en fonction de l'importance des parts d'eau, de l'étendue de la propriété foncière et de la situation des terres par rapport au réseau d'irrigation. En effet, le système de distribution de l'eau en vigueur impose une irrigation discontinue dans l'espace. La topographie ne comptant pour rien dans l'attribution de l'eau, celle- ci saute le vaste espace entre deux pour irriguer les parcelles d'un même propriétaire, généralement dispersées sur le terroir irrigué. Au gré de la dispersion des parcelles d'un même propriétaire d'abord, et de tous les autres propriétaires ensuite, résulte un incessant transport d'eau; d'où des pertes d'eau importantes sous les effets conjugués de l'évaporation, de l'infiltration, des déficiences du réseau et même du vol d'eau. Encore faut-il préciser que ce rapprochement n'inclut pas les terres des propriétaires/ exploitants ne disposant d'aucun droit d'eau.

Tableau 10.3 *Rapprochement parts d'eau et besoins en eau en m^3.*

Total des parts d'eau (m^3/16 jours)	*Total des besoins d'eau (m^3/16 jours)*	*Déficit (m^3/16 jours)*
18,155	252,250	234,095

Selon toutes les indications, l'écart entre les besoins en eau et les ressources disponibles a de plus en plus tendance à s'élever. Suite aux divisions successorales, la propriété de l'eau et de la terre est soumise à un émiettement incessant augmentant ainsi l'écart entre les besoins et les parts d'eau disponibles d'une part. Et, d'autre part, face aux sécheresses prolongées de ces dernières années, la portée de la seguia pour réduire le décalage (spatial ou temporel) entre les ressources en eau et les besoins est très limitée. En effet, il convient de rappeler que le barrage en tête de ce réseau traditionnel n'a qu'une fonction de blocage et de dérivation et non de régulation et de stockage de l'eau. En outre, cette technique n'est efficace que dans la dérivation de faibles et moyens débits, tandis que les fortes crues détruisent la dérivation et engorgent l'entrée du réseau. L'eau n'est donc utilisée qu'au moment où le régime de l'oued assure sa présence avec des débits modérés. Enfin, face à l'irrégularité interannuelle climatique et hydrologique (5 ou 6 années sèches succédant à 1 ou 2 années humides), la technique de la seguia n'autorise aucune correction temporelle ni spatiale. Ces différentes raisons expliquent donc largement l'insuffisance voire la pénurie d'eau à laquelle la population du bassin tente d'apporter des réponses.

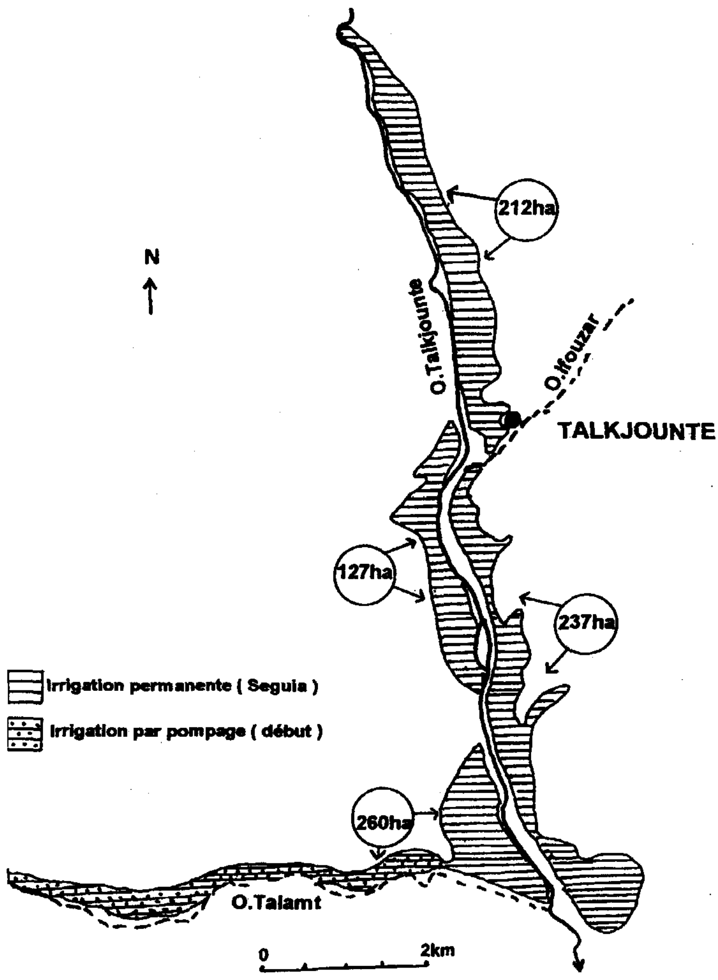

Figure 10.6 *Les périmètres irrigués par le système de séguia.*

10.2 Mutations du système et tentatives d'adaptation

Les entraves à une utilisation efficiente des eaux de Talkjounte pour une exploitation agricole viable dont les causes sont multiples ont également des effets et des conséquences qui ont suscité des réactions ou des tentatives d'adaptation multiples:

En liaison directe avec la question qui nous occupe, l'insuffisance de l'eau, les villageois ou du moins une partie des villageois (les ayants-droits aux eaux des seguias) essayent d'augmenter les disponibilités en eau en procédant à des réaménagements du réseau d'irrigation afin d'en augmenter l'efficience. C'est dans ce cadre qu'un important tronçon du canal a été bétonné grâce à l'appui de la commune rurale. Cet appui ne fait pas l'unanimité, puisque l'eau ne profite qu'à une partie des villageois d'autant plus que pour d'autres le bétonnage limite les infiltrations bénéfiques aux arbres le long des canaux.

Dans le même ordre d'idées, nous pouvons placer également l'apparition, durant les six dernières années, des puits et du recours au pompage des eaux de la nappe en aval du bassin. Les superficies dominées par les six puits en place sont réduites, ne dépassant guère 6 ha, ce qui est infime par rapport aux terres desservies par les seguias. Mais ces innovations constituent des réponses individuelles qui se multiplient rapidement face à l'insuffisance et à la pénurie des eaux superficielles.

Face aux effets du même problème, insuffisance de l'eau, à la difficulté d'accès à la terre et aux droits d'eau et à la pénurie de la main d'œuvre, les systèmes de culture et de production subissent, selon les villageois eux-mêmes, de profondes mutations. Les cultures annuelles exigeantes en irrigation et en main-d'œuvre font de plus en plus place à l'arboriculture: olivier, amandier et surtout le caroubier générateur de revenus substantiels.

Enfin, les difficultés d'exploitation et d'accès à la terre et à l'eau ont incité une partie non négligeable de la population à changer de secteur à la fois géographique et ou d'activité, à émigrer vers la plaine du Souss ou vers les autres régions du Maroc définitivement ou de façon saisonnière. Ce dernier mouvement intéresse ainsi de façon régulière plus de 34 % des chefs de foyers touchés par l'enquête.

Ces mouvements de la population permettent certes d'alléger la pression sur les ressources limitées du bassin, mais en retour ce dernier souffre d'une pénurie grandissante en main- d'œuvre se traduisant au niveau des seguias par les difficultés d'entretien du réseau et à long terme par les risques de dégradation du système.

10.3 Place de la seguia dans la vie économique et sociale de la société locale

On peut estimer la rentabilité de la technique seguia à partir d'une comparaison entre le coût de construction et d'entretien du réseau d'irrigation d'une part, et la production économique due à la présence de ce réseau d'autre part.

10.3.1 Coût de la seguia

Selon la fiche technique préparée par la direction provinciale d'Equipement (D.P.E) de Taroudant, le coût de construction/réfection de la Seguia est estimé à : 359.085,00 DH, répartis comme suit :

Tableau 10.4 *Coût de construction/réfection de la seguia.*

Rubriques	*Montant par tranche en DH*	*Montant global (3 tranches)*
Main-d'œuvre	37 504,80	112 514,40
Matériaux	78 190,20	234 570,00
Carburant	4 000,00	12 000,00
Total	119 695,00	359 085,00

La construction de la seguia en béton armé est donc estimée à 119 700 DH par tranche, ce qui donne une somme globale de 359100 DH, soit 462,16 DH par foyer.

10.3.2 Rendement économique de la seguia

Les cultures

Tableau 10.5 *Ventilation des surfaces cultivées par culture.*

Cultures	*Surface en Hectares*	*%*
Blé	300	34.3
Orge	500	57,2
Fève	60	6,9
Légumes	10	1,1
Autres	4	0,4
Total	874	

La surface irriguée est de 874 hectares soit 3 % environ de la surface globale du bassin versant. La superficie irriguée est limitée aux rives de l'oued sur une bande très étroite. Le faible débit de la source et la précarité du système d'irrigation en sont les causes objectives. La productivité est également faible :

Tableau 10.6 *La productivité des cultures.*

Cultures	*Productivité en Quintaux (q) par ha*
Blé	14
Orge	12
Fève	15
Légumes	180

De ce fait, la production totale des surfaces irriguées serait de :

Blé	: 300 x 14	= 4200 q
Orge	: 500 x 12	= 6000 q
Fève	: 60 x 15	= 900 q
Légumes	: 180 x 10	= 1800 q
Autres	: 4 x 10	= 40 q

C'est une production qui ne dépasse donc pas le stade de la subsistance sans même atteindre l'auto - suffisance de la consommation locale. La production totale ne dépasse guère 11,140 q en céréales et 1800 q en légumes. La ration individuelle s'élève par conséquent à 1,9 q par an, soit l'équivalent de 487 Dh et 231 kg de légumes pour chaque foyer en une année.

L'activité agricole sous ses différentes formes (labour, moisson, élevage) est presque l'unique activité productive. Elle change de rythme et de nature selon les saisons. L'été étant la saison la plus animée. Les activités se répartissent ainsi :

Tableau 10.7 *Activités agricoles et main-d'œuvre mobilisée.*

Activités	*Main-d'œuvre*		*Total*
	Hommes	*Femmes*	
Labour	250	0	250
Moisson	1500	900	2400
Autres activités	1200	1800	3000

L'élevage

Il constitue la deuxième activité productive et dépend en grande partie des disponibilités en eau de la seguia, laquelle irrigue les cultures fourragères nécessaires à la nourriture du cheptel notamment durant les périodes de sécheresse d'une part et d'autre part, la seguia assure l'eau nécessaire à l'abreuvage du bétail.

Le cheptel comporte 7200 bêtes réparties comme suit :

Caprins	:	3700
Ovins	:	1200
Bovins	:	1600
Autres	:	700
Total	:	7200

Compte-tenu de la population totale ce nombre est très faible, la répartition par foyers est également très inégale ; elle varie dans un rapport de 1 à 200 bêtes par foyer.

Considérant cette faible productivité des produits agricoles, l'exode vers les villes de la région et vers la vallée du Souss est un phénomène apparent qui prend de l'ampleur surtout parmi les jeunes. La précarité des moyens et des techniques de la production oblige les habitants à fournir d'énormes efforts pour une rentabilité infime et incertaine. Toutes les formes et sources de travail sont mobilisées, y compris l'emploi des enfants qui participent activement à l'économie familiale. Ils exercent en permanence des tâches dures au détriment de leur scolarisation, notamment les filles qui quittent souvent l'école avant la fin des études primaires.

10.4 Quelle diffusion de la technique seguia, vers les périmètres villageois

Selon le résultat d'estimation des productions agricoles (coût et production), il nous parait que les cultures pratiquées dans le périmètre de Talkjounte sont en quelque sorte justifiées financièrement. Certes, la valeur économique des productions réalisées semble infime et parfois ne couvre même pas les dépenses engagées. Pourtant, la population continue de produire et d'entretenir la vie agricole parfois au prix d'injection d'argent gagné dans d'autres secteurs économiques et dans d'autres régions: plus de 30 % des chefs de foyer émigrent de façon saisonnière !

Cette situation soulève des interrogations quant à une évaluation des aménagements hydro-agricoles en termes économiques et financiers ? Peut-on véritablement baser des décisions sur une telle évaluation? Dans le casqui nous occupe, la poursuite de l'agriculture ne peut certainement pas se justifier par une évaluation économique mais plutôt par un bilan social visant le maintien sur place d'une population que tout invite au départ, à l'émigration. A partir d'une perspective plus large et à long terme, la poursuite de l'agriculture et l'entretien des techniques villageoises d'utilisation des eaux doivent être justifiés et justifiables par un bilan environnemental ou l'entretien d'un paysage construit, d'un bassin versant contre la dégradation dont les conséquences se répercuteraient directement sur la riche vallée du Souss et ses coûteux aménagements hydrauliques.

10.5 Conclusion

Les petits périmètres, comme Talkjounte, implantés en amont de la basse grande vallée du Souss apparaissent comme une alternative d'avenir qui pourrait contribuer à alléger certains des problèmes inhérents au développement de l'agriculture irriguée, et aider la population à trouver sur place une partie des éléments nécessaires à sa survie

Il ne s'agit nullement de diffuser la technique de la seguia, laquelle est déjà largement connue au Maroc et au Maghreb. A notre avis, il s'agit plutôt de favoriser et privilégier des réalisations techniques à faible coût, correspondant à l'aménagement d'un périmètre limité et partant maîtrisable par une communauté réduite selon les règles qui régissent le fonctionnement de cette communauté sans exclure la possibilité de remettre en cause certains legs tels que l'appropriation privée de l'eau qui menace, dans l'exemple de Talkjounte, le devenir du périmètre.

La réduction des coûts de réalisation ne résultera pas forcément de l'abaissement du niveau technique et technologique des aménagements. Elle proviendra plutôt des diminutions liées à la prise en compte de l'intégration des techniques existantes, du recours au savoir-faire local et de la participation des agriculteurs concernés.

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11 TOOL FOR DECISION-MAKING ON WATER HARVESTING TECHNIQUES IN ARID ZONES

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Abstract

In semi-arid and arid zones water demand regularly exceeds water supply. This can reduce local water consumption by the human and animal population and/or lead to a depletion of groundwater resources. Water harvesting techniques may play an important role in the use of scarce water resources, by retaining surface water and storing it for production purposes. Because of their extensive rooting system tree crops such as olives, can make the best use of these systems. However, one should investigate what effects these systems in upper zones have on water supply in lower parts and how scarce financial resources could be optimally allocated to investment in land and water management. A decision support tool has been developed, consisting of four main parts:

a) First an analysis is made of the hydrological system and water balance at regional and watershed level. For both areas, the water demand will be confronted with water supply, to assess the need for various types of WHT. Subsequently an analysis of actual erosion and sedimentation will be made.
b) Secondly a screening is made of the various types of WHT, with their technical specifications, costs, and listing of their effects on local and downstream water balance components, on erosion and sedimentation and on production.
c) Thereafter a thorough assessment of these effects is made. Quantitative field data are required of the effects for selected WHTs and watersheds. These data will then be used to calibrate hydrological and erosion models developed for watershed level analysis. With the models and field, it can be calculated how much additional water and nutrients are available for local production (thanks to WHTs), and with the use of response functions local production increases can be calculated. Information will also be generated about effects on downstream water balance components and sedimentation.
d) This detailed impact assessment can then be used for the evaluation of the WHTs at the level of individual measures, (sub-) watersheds and regions, using economic evaluation methods, such as Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA).

The WAHIA project has focused its attention mainly on the third and the fourth part. This final paper gives a general overview of the decision support tool for land and water management and it will be briefly illustrated with an example from the Oued Oum Zessar watershed near Médenine in southern Tunisia.

Keywords: decision support, impact assessment, water harvesting, economic evaluation, arid zones

11.1 Introduction

11.1.1 Objectives of tool for decision-making in water harvesting

In semi-arid and arid zones water demand generally exceeds water supply, and in particular during dry seasons in extremely dry years. This can either lead to reduced 'water consumption' (e.g. more extensive agriculture, migration) or to a depletion to groundwater, or both. Water harvesting techniques can play an important role in optimal use of these scarce water resources. However, one should assess how scarce financial resources could be optimally allocated to investment in different water harvesting techniques. In situations, where the population is moving towards the plains and urban centres, it maybe better to invest in groundwater recharge structures then in hillside lakes for agricultural production within the mountain zone. The tool for decision-making in water harvesting at watershed level, could for different options give insight in cost-benefit ratios, in less quantifiable effects and in trade-offs.

11.1.2 Framework within which decision-making takes place

The scope for the expansion of water harvesting systems is largely determined by agro-ecological conditions, by socio-economic circumstances and by national and regional political priorities and policies.

The most important *agro-ecological conditions* to consider are the effective rainfall, the soils and the topography. Because of the reference areas defined by the WAHIA project in south-eastern Tunisia and south-western Morocco (Souss basin), this tool is mainly focused on sub-tropical arid zones, with winter rains. Important for WHT is the number of high intensity rain showers that produce runoff.

Requirements with regard to soil properties vary according to the main components of the water harvesting system: the catchment area or impluvium, the cultivated area or terrace, and the structure constructed to retain the runoff. As a general rule, soil properties in the catchment part of the system should be conducive to produce runoff (e.g. shallow soils, clayey soils, crusted soils). On the other hand soils in the cultivated part of the system should be deep and have a satisfactory available water holding capacity. The soil used for building permanent structures should have good structural properties and withstand erosion.

For water harvesting sloping land is a prerequisite, and slope length a major factor. Depending on effective rainfall and runoff rates, different ratios between catchment and cropping area (CCR) could be determined. While Chahbani (1996) argues that the ratio should be < 5 for areas with about 200 mm and < 10 for areas with 100 mm rainfall, in arid zones typical CCR's usually range from 10 up to 50 or higher (to cater for dry years). For efficiency reasons impluvia then require long slopes.

There are also important *socio-economic factors* that determine whether WHT could be promoted in certain areas. A major factor is often population density. Arid zones are generally sparsely populated, and a certain minimum population density is required for investment in services and infrastructural works. Also important is the trend of population growth, including migration. Reasons for out-migration are usually the limited job opportunities in arid zones (push factor), and the attractiveness of jobs in service and industrial sectors in urban areas (pull factor).

The potential for water harvesting techniques also depends on *regional development policies.* A choice has to be made among others between more water in upstream or in downstream areas. In many regions rural-urban migration has led to a population decline in upstream rural areas. A lower rural population leads to diminishing rural infrastructure and services and quality of life. Realising the drawbacks of accelerated urbanisation, government policies may focus more on rural development

Because of the common property nature of many water resources, there should be a clear rights and entitlements defining who has access to water resources in different places and at different times. Laws and regulations should ensure that customs and traditions are respected and all water uses and stakeholders are included. Large-scale water harvesting in upper watersheds may have a negative influence on overall water supplies in lower parts, but also a mitigating influence on flood hazards.

The market prospects for additional crop production in upper watersheds should be investigated. It often concerns remote areas, where the costs of transport greatly reduce farm gate prices. High valued, storable produce is preferred.

11.1.3 General structure of tool

The tool consists of four main parts:

a) There is first a need to analyse the hydrological system and water balance at regional and watershed level. Regions and watersheds can be sub-divided in upper parts, where WHTs can be established, and lower parts that may be affected. For both areas, water demand will be confronted with water supply, to assess the need for various types of WHT. And an analysis of actual erosion and sedimentation in the areas will be made.
b) Secondly a screening is required of these various types of WHT, with their technical specifications, costs, and listing of their effects on local and downstream water balance components, on erosion and sedimentation and on production.
c) Thereafter a thorough assessment of these effects is required. Thereto quantitative field data are required of the effects of a sample of selected WHTs and (sub-) watersheds, which will subsequently be used to calibrate hydrological and erosion. This should result in data on the additional water and nutrients available for local production (thanks to WHTs), and through the use of response function in information about local production increases. And it should result in information about effect on downstream water balance components and sedimentation.
d) This detailed impact assessment can then be used for the evaluation of the WHTs at the level of individual measures, (sub-) watersheds and regions.

In the four next chapters these parts of the tool will be discussed in more detail. An example will be elaborated for the Oued Oum Zessar watershed in section 11.6.

11.2 The hydrological system

11.2.1 Water balance at (sub-) watershed level

On the basis of effective rainfall and water supply studies on the one hand and the actual demand for drinking water, agriculture and industries on the other hand, one can estimate whether local water resources are depleted or still available 'in excess'.

Hydrologists can assess to what extent surface water resources are effectively used, by calculating the amount of water used and the amount passing the outlet of the watershed or entering the sea. Hydro-geologists can help in verifying the effective use or depletion of the ground water resources by means of monitoring studies (e.g. use of MULTIC package for Zeuss-Koutine watershed in south Tunisia).

A distinction has to be made first between the target areas for implementation of water harvesting techniques and the areas downstream of these structures in lower watersheds. On the basis of aggregate data on precipitation, evapotranspiration and changes in soil and groundwater stocks an aggregate water balance can be established, for upper and lower parts of watershed:

Upper part: $P = (Rf\text{-}Rn) + ET + D + dS$ (Equation 1a)

Lower part: $P + Sf + Ir = (Rn\text{-}Rf) + ET + (X\text{-}D) + dS$ (Equation 1b)

where: P = Precipitation, Rn/Rf = Run-on and run-off (lateral overland flow), ET = Evapotranspiration, D = Drainage (percolation) and dS = Change in storage in rootzone of soil, Sf = Sub-surface flow, Ir = Irrigation from channeled surface flow, X = Extraction from groundwater.

Water supply factors

The water supply for the upper part of the watershed predominantly consists of precipitation (P), on the water harvesting plots supplemented with run-on (*Rn*). In case some wells have been drilled in these upper parts, this groundwater extraction should be included. In lower watershed areas precipitation can be supplemented by various components:

a) by overland flow (Run-off) from upper parts, which could partly be channelled through ephemeral rivers and irrigation channels (*Ir*)
b) by sub-surface flow (*Sf*) from upper-parts, surfacing (as sources) in lower parts
c) by net extraction (*X*) from groundwater resources through wells.

WHTs may negatively affect the first component (a), but positively influence the other two components. Because of large fluctuations in annual rainfall in arid and semi-arid areas, one does not only consider an average rainfall year, but focuses on dry years and on sequences of dry, average and wet years and consequences of these heterogeneous rainfall patterns. Besides one has to consider the occurrence of individual rainstorms. Usually only a few storms per year produce considerable runoff and erosion.

Water demand factors

In upper watershed areas water demand will largely consist of water requirements for human and livestock population and water for agricultural purposes (mainly incidental water gifts for tree crops and vegetables in home gardens). In lower watershed areas one will encounter the same water uses, but to this should be added water for irrigated agriculture (vegetables, cereals and tree crops) and in the urban areas and tourist resorts water is also needed for urban and tourist population and for trade and industrial uses. Table 11.1 provides some general norms, which of course vary for different areas, depending on local traditions, livestock breeds, crop species, etc.

Table 11.1 *Norms for water demand*

	Unit	*Drinking water*	*Other(+ losses)*	*Total*	*Total; m^3 $head^{-1}$ yr^{-1}*
Rural population	Lt $capita^{-1}$ day^{-1}	70	30	100	36
Urban pop. Middle inc.	Lt $capita^{-1}$ day^{-}	160	60	220	80
Urban pop. High income	Lt $capita^{-1}$ day^{-}	220	80	300	110
Tourist resorts	M^3 $room^{-1}$ day^{-1}			400	150
Industrial water use				varies	-
Cattle	Lt $head^{-1}$ day^{-1}	40	15	55	20
Dairy cattle	Lt $head^{-1}$ day^{-1}	80	30	110	40
Sheep and Goats	Lt $head^{-1}$ day^{-1}	6	2	8	3
		Water use	Losses	Total	M^3 ha^{-1}
Irrig. Vegetabl. 3-4 mth	Mm	550	110	660	6,600
Irrig. Cereales 5 mth	Mm	600	120	720	7,200
Irrig. Tree crops 12 mth	Mm	900	150	1050	10,500

Sources: ILACO, 1981; BKH, 2000.

11.2.2 Land use changes and water balance

The implementation of WHTs will automatically imply some land use changes. The watershed slopes previously used for grazing of (small) ruminants and consisting of shrub- and grassland will become impluvia with little vegetation and with an upper soil layer conducive to run-off. The terraces, constituting a relative small part of the watershed areas will on the other hand become 'cropland', with trees or annual crops. These land use changes have repercussions for evapo-transpiration, infiltration and runoff. To obtain a rough idea how these components of the water balance will change as a result of these land use changes, the watershed can be dis-aggregated by land use with actual and future scenarios. Table 11.2 shows an hypothetical example, whereby a (shrub and) grass area is transformed in a water harvesting scheme with a tree terrace and it (rather bare) impluvium. It shows how water balance components change and what effects it can have on downstream water availability. Next to average years, dry and wet years should be considered too.

Table 11.2 *Water availability in upper part watershed, with and without WHT*

Land use: *Coverage: ha*	*Shrub*	*Grass*	*Bare /Impl*	*Rainfed Ann.l*	*WH-terrace With trees*	*Total*	
Actual area	300	550	100	50	0	1000 ha	
Future area	270	250	350	30	100	1000 ha	
						Average	
Water balance: mm						*Actual*	*Future*
Precipitation (aver)	200	200	200	200	200	200	200
Evapotransp.Actual	100	90	50	100	300	89	100
Deep percolation	60	50	40	40	50	52	49
Direct runoff (net)	40	60	110	60	-150	59	51
						Average	
Made available via run-off and infiltration/deep percolation (storage) at outlet in:							
Dry season 1	30	30	20	30	-20	29	22
Wet season 1	70	80	130	70	-80	82	78

Source: Adapted from de Graaff, 1996.

11.2.3 Erosion, sedimentation and nutrient balances

WHTs have also effect on soil erosion by water, and the resulting sedimentation downstream. For an assessment of actual soil erosion use can be made of the Morgan, Morgan and Finney model (Morgan et al., 1984). This makes a clear distinction between on the one hand the soil detachment capacity of rain showers and on the other hand the transport capacity of the resulting run-off. This could be incorporated in a Geo-Information System with a digital elevation model (DEM), in order to be able to obtain spatially differentiated data on erosion and sedimentation. On the basis of soil sample analysis from the impluvium, the terraces and other sites an impression can be obtained of the nutrient harvesting of the WHTs.

11.3 Water harvesting techniques

Classification of Water Harvesting Techniques
Water harvesting systems consist of the collection and concentration of run-off, for the purpose of improving plant production in arid and semi-arid regions. WHTs constitute structures that enable the collection and concentration of runoff. WHT could be distinguished on the basis of:

a) *Scale of operation or catchment area:* The scale of operation could range from a small sub-catchment of a few hectares managed by an individual farmer (e.g. jesr in Tunisia), to a large watershed or whole river basin. In the latter situation the focus is on the provision of sufficient irrigation water in the central valley of such a basin (e.g. Souss basin in Morocco). The smallest scale consists of rooftop or tank collection of drinking water.
b) *Form of run-off:* A distinction can be made between surface runoff (overland flow or channel flow) and sub-surface flow (throughflow and groundwater flow).
c) *On-site or downstream water use.* The water collected can be stored in an artificial lake (e.g. lac collinaire) or in the soil profile, and be used locally. Or the water is transported by canals or allowed to percolate to deeper soil layers in order to be used in downstream areas.
d) *Size and type of structures*: either small simple structures to be constructed by farmers themselves or large (dam) structures to be established by public agencies or farmer' organisations. Simple structures can either be more or less permanent, or only temporary, lasting one season and being washed away after heavy floods (e.g. often in spate irrigation).
e) *Purpose.* Water can be used for agriculture, for drinking water for the human and/or animal population or for industrial purposes. The replenishment of ground water aquifers will usually serve several purposes.

Pacey and Cullins (1986), Reij et al. (1988) and Barrow (1987) provide a good overview of the various types of water harvesting methods.

Technical parameters and cost elements for WHTs in different situations
The most characteristic aspect of water harvesting systems is the permanent or temporary dam structure, usually with a spillway. On the basis of technical design criteria the type and size of dam and spillway can be calculated. Subsequently the labour (skilled and unskilled), machine and material inputs (local or imported) required can be determined, which form the basis for the cost calculations. Other costs involved could be the site preparations and loss of income from the catchment.

Potential beneficial effects of WHT in different situations
The WHT allows the cultivation of annual and perennial crops in situations, where without any WHT production is not feasible. The same techniques, but also special WHTs (e.g. groundwater recharge structures), have important effects on groundwater replenishment, and water use downstream.

11.4 Impact assessment procedures

11.4.1 Impact assessment and evaluation framework

Options
Once the agro-ecological and socio-economic setting has been analysed, and objectives, resource endowments and constraints of major actors in land and water management are known, various options for WHTs can be formulated that contribute to overall objectives. This is the first step in the decision-making framework (Table 11.3).

Table 11.3 *Steps in decision making framework and impact assessment*

Steps		*Issues*	*Type of analysis*
1	Decision making framework		
1.1	Options	Alternative WHTs or combined	Defining alternative scenarios
1.2	Role of actors	Determining target groups	Particip. anal./conflict resolution
1.3	Evaluation criteria	Criteria and criteria weights	Select. Crit../Attributes/Weights
2	Impact assessment		
2.1	Inputs by actors (lab./mat.)	Investment and recurrent costs	Cost analysis
2.2	On-site effects	Effects on soil (nutr.) and water	Yield response
2.3	Downstream effects	Effects on sedim. and streamflow	Impact downstream changes
		Effects on groundwater	Impact downstream
2.4	Other and overall impacts	Other effects and multipliers	E.g. pesticide
3	Evaluation (see section 5)		

Source; de Graaff, 1996

When the options or combination of components are formulated, attention should be given to selection of relevant target groups for these options. For each option one needs to spell out which groups of actors are likely to participate in or likely to be affected by the option (Participation analysis). It may also be necessary to assess whether conflicting views could be reconciled, by redistributing costs and/or benefits. This could be in the form of charges (e.g. for water) or incentives or support services.

In the decision-making framework one has already to indicate the main criteria and attributes that will be applied in the evaluation of alternative options or scenarios. A WHT activity is feasible when it scores sufficiently high on the three main criteria: efficiency, equity and sustainability and when it is financially attractive to the main actors (local and/or downstream) concerned.

Impact assessment starts with the identification of all direct and indirect effects of WHTs. For each option the inputs have to be assessed for the actors that incur costs and/or derive benefits from it. Subsequently the effects need to be quantified and valued, where possible. For the overall impact assessment, field and actor level data need to be aggregated to watershed and regional level (upscaling).

For the WHT options one should first determine and quantify the on-site physical effects on the soil water and/or nutrient balances and the yield response of these changes. Thereafter one should analyse how the changes in on-site water balance and erosion affect sedimentation, water supply and production downstream. These off-site effects require an aggregation of all water supply related effects on watershed level, and can only be quantified when detailed hydrological research has been undertaken. If not, the magnitude of these effects may be presented on an ordinal scale (e.g. a very strong/strong/moderate/slight/very slight reduction of sedimentation or improvement of Qmax/Qmin ratio). The remainder of this section discusses impact quantification.

Effects of WHTs on water balances at local level

In order to assess the effects of water harvesting techniques on crop production, one has to assess the following:

a) How do the WHTs affect the water balances, and subsequently
b) how does the reduced water stress influence production?

In this section a spreadsheet module is used for water harvesting impact assessment.

For the assessment of benefits related to more optimal water management, information is required about the response of crops to water shortage (and in some cases to excess water). For this a response function is required. In production situations where water is the most limiting factor, one can relate the production (yield response) to the evapotranspiration, as follows (Doorenbos and Kassam, 1979):

$$1 - Ya / Ym = Ky (1 - ETa / ETm) \qquad \text{(Equation 2)}$$

where: *Ya and Ym are actual and maximum yield; ETa and ETm are actual and maximum evapotranspiration and Ky is the yield response factor.*

The yield response factor depends on the crop and the growing stage, and has been calculated in many cases on the basis of experiments.

Crop growth models are often used for the analysis of effects of water availability on crop production. The simpler, spreadsheet, method makes use of the water balance method of Thornthwaite and Mather (1955) and the response function of Doorenbos and Kassam (1979). The procedure is discussed in de Graaff (1996) and applied in Chapter 8.

Effects of WHTs on water balances at watershed level

The upscaling of effects on the waterbalance from field to watershed level is complicated, but an attempt can be made, through the following three steps:

1. Transform field - into (sub) watershed level water balance:
   Field level (LUST): $P = ET + (Ro + Rs) + (D) + dSM$
   Watershed level: $P = ET + (QF) + (BF + dG)$

2. Divide (sub)watershed in hydrological units, with each three stores:

- the root zone, supplying water to the plants
- the deep soil, supplying the groundwater
- the streams (and canals) for lower watershed parts

3. Use models with GIS for water distribution over stores
   Depending on permeability and saturated conductivity water will contribute to runoff, rootzone or deep percolation, and hence at watershed level to *QF*, *ET* and/or *BF +dG*.

Effects of WHTs on nutrient balances and production

Water harvesting techniques usually have also important nutrient harvesting effects. Often no use is made of manuring and chemical fertilisers, and terrace fields are nevertheless cultivated for decades (Niemeijer, 1998). In order to assess the effects of WHT on harvesting of nutrients, that contribute to crop production, one has to assess the following:

a) how do the WHTs affect the nutrient flows, and subsequently
b) how does the nutrient harvesting influences production.

To assess how WHTs affect the availability of the macro-nutrients (top)soil and/or plant samples should be analysed. From these samples indications can be derived about the total organic matter (C) and nutrient (N, P and K) content. One can draw up nutrient balances for both the situation without and with water harvesting techniques and determine the change in the nutrient balances (or compare nutrient status on impluvium and terrace).

A nutrient balance for nitrogen is composed of the following inputs and outputs:

Fertil+Manure+Deposit+Fixation+Sediment - Product-Residu-Leaching-Gases-Erosion = Balance (3)

The uptake-yield relationship of nutrients consists of a curve, that is initially linear, under low uptake levels, and that subsequently flattens off at higher uptake values. The initial yield response or 'initial nutrient use efficiency' (INUE in kg dry matter or harvested product per kg nutrient supply) can be derived for nitrogen in grain production from the formula (Lövenstein et al., 1993):

$$INUE=\{ 1/(N_{grain}+(W_{straw}/W_{grain})*N_{straw})\} /(\%DM/100) \qquad \text{(Equation 4)}$$

where: N_{grain} and N_{straw} are the minimum N concentration in grain and straw (about 1 % and 0.4 % respectively); W_{grain} and W_{straw} the dry weight (in kg ha^{-1}) and DM the dry matter content in grain (about 85 %)

Information is available about the minimum and maximum nutrient concentration in harvested products and residues. The yield response to one kg N, at sub-optimal levels of fertiliser application, can then be obtained by multiplying the recovery fraction with the INUE.

To assess the effects of nutrient harvesting on production, one can also measure the depth of respective annual sediment layers; e.g. a last, upper, layer of 5 cm and an underlying layer of 45 cm from the previous nine years. For these layers and with knowledge about the bulk density one can measure and calculate the total nitrogen and P(Olsen) content. It can be assumed that 2 % of N becomes available every year through mineralisation and 50 % of P-Olsen may be regarded as available to plant growth. With crop uptake ratio for grains of for example 0,026 for nitrogen and 0,005 for phosphorus, a net (minus leaching, etc) available 20 kg ha^{-1} of nitrogen and 5 kg ha^{-1} of phosphorus gives N and P limited yields of 770 kg ha^{-1} and 1000 kg ha^{-1}.

Other effects

Apart from water and nutrient balance related effects on production, WHTs can bring about several other effects. It can influence water quality, and in particular salinisation, for example as result of over-exploitation of groundwater. Pesticide residues can also influence water quality. Other important effects, identified in the Tunisian case study watershed, are the increase in arable land, as a result from reduced flooding hazard. And changes in land use and cropping systems.

11.5 Evaluation

Evaluation procedures

When all impacts of the respective WHTs have been assessed, the attainability assessment or evaluation can take place. It starts with a financial analysis to assess the possible results for the actors (Table 11.4). It is then followed by an economic analysis for the whole watershed as its impact area.

For each WHT option the stream of effects (costs and benefits in physical terms) should be shown that the actor groups are likely to derive from that option. Valuation techniques should then be applied to arrive at financial values, using conventional, surrogate or artificial market prices. If all effects can be valued in monetary units, a financial cots-benefit analysis (FCBA) shows to what extent the WHTs are financially attractive for this group, and whether financial incentives may be required. Where certain effects cannot be valued in monetary terms, these effects can be provided in physical or ordinal terms. In financial analysis break-even analysis may then be applied, to review under which conditions the WHTs are attractive for the respective actors. A weight can be calculated for respective groups of actors in order to obtain aggregated financial results.

Table 11.4 *Steps in evaluation*

3. Evaluation	*Issues*	*Type of analysis*
3.1 Financial analysis	Financial results actors	FCBA
3.2 Efficiency assessment	National econ. (monetary) impacts	ECBA
3.3 Equity considerations	(Re)distribution aspects	SCBA
3.4 Sustainability	Conserving land and water resources	ECBA and/or MCA
3.5 Trade-off analysis	Score on all criteria/role of incentives	CBA and/or MCA

Source: de Graaff, 1996.

The financial values are then transformed into economic values by means of inclusion of transfer payments and externalities and by using economic prices. It then becomes apparent to what extent the WHTs are also important from a national economic point of view and whether this makes use of incentives acceptable. Whenever possible downstream and other external effects of water harvesting should be included in this economic cost-benefit analysis (ECBA), by quantifying these effects and valuing them in monetary terms. One also refers to Extended CBA in case of environmental effects.

The different WHTs may have a different impact on intertemporal, intratemporal and spatial equity. Therefore emphasis should be paid to differences in impact: on the present and future generations; on the various social groups; and on the upland and downstream communities. This can be achieved through the use of social cost-benefit analysis (SCBA).

However, when important effects pertaining to sustainability cannot be valued in monetary terms and therefore cannot be adequately included in the cost-benefit analysis, multi-criteria analysis (MCA) can be used instead. Separate attributes of the conservation criterion should be spelt out and weights should be attached to these attributes. CBA and MCA can also be combined. Multi-criteria analysis could then incorporate scores on efficiency (and equity) criteria obtained by cost-benefit analysis.

11.6 Application of tool for Oued Oum Zessar watershed in Tunisia

The tool is here applied, asexample, for the Oued Oum Zessar watershed in which in the last ten years many WHTs have been established, in particular jessour and tabias, and recently also many groundwater recharge structures. Since the project largely focused on the last two steps of the tool, only these steps will be discussed.
The impact assessment and evaluation method is illustrated at two levels:
a) at the level of the individual WHT , here the Amrich jessr.
b) at the level of the watershed, here the Oued Oum Zessar watershed.

11.6.1 Impact assessment and economic evaluation of individual WHT

In this example attention is focussed on the on-site effects and on the financial analysis of a jessr.

The individual WHT
The Amrich jessr was established in 1965 and consists of an 8 ha impluvium and a 0.275 ha terrace, created by a 113 m long dam, with width of 5 m and height of 3 m.
On the terrace 5 olive trees and one fig tree have been planted. Thanks to the WHT the olive trees produce on average 60 kg olives per year (Table 11.5).

Table 11.5 *Characteristics of Jessr of Amrich*

Site	Impluvium	Terrace	CCR-ratio	Tree numbers	Plant distance
	8 ha	0,275 ha	29	5 olives + 1 fig	17 x 17 m
Dam	Length	Width	Height	Volume dam	Investment costs
	113 m	5 m	3 m	1695 m3	640 DT ($ 640)
Terrace	Soil depth	Soil volume	Water storag	Tot. water stor.	Sat.hydr.conduct.
	Av. 1,4 m	3,500 m3	15-25 %	293 mm	Ks = 55 mm $hour^{-1}$

Inputs by actors
Construction costs of the dam in actual prices were estimated by multiplying volume of earth movement with volume and wage rate per manday, amounting to 642 DT. Maintenance costs were estimated at 18 DT and the without case was considered as extensive grazing, producing 100 UF per ha on average for 'normal' rainfall year.

On-site effects on water balance
In order to assess how the WHT contributes to the improvement of water supply to the olives trees, measurements were undertaken on the various components of the water balance. Rainfall intensities were recorded and maximal and actual evapotranspiration were calculated. To assess water availability for the olives soil texture and water retention on the terrace were calculated. Since the number of rainfall events is very limited and variable, the runoff from the impluvium was determined on an event basis, through use of mobile rainfall simulators (Chapter 5).

Total rainfall during the three year period April 98-May-'01 was about 500 mm (160 mm per year). Runoff-coefficients ranged from 0-84 %, and were on average less than 10 %. Considering initially dry soils (most common) it was assessed that a total of 25 rain showers (together 200 mm) produced runoff. In this period the runoff increased the water available on the terrace with 618 mm or more than 200 mm per year (Tanghe, 2002). It was found that the

CCR in average years would only have to be about 8, but the subsequent two extreme dry years (2000 and 2001) have shown the advantage of the actual large CCR, of in this case 29.

With the results of the water balance measurements a spreadsheet model has been used (de Graaff, 1996) to translate the water balance effects into effects on yields. Hereby use is made of the Doorenbos and Kassam (1979) yield response formula. Because of the large annual rainfall variability and the bi-annual bearing characteristics of (olive) trees, the yield response factor has been divided in fruiting and vegetative component (Chapter 8). This method was tested for a 5 year data set in Sfax region and showed a high correlation coefficient between simulated and measured yields. The application for the Amrich jessr showed very low yields for the extremely dry years 2000 and 2001, during which the farmer had in fact not harvested at all.

On-site effects on soil erosion and sedimentation

Next to effects on the water balance attention was also paid to sediment transport, which had originally helped to form the terrace and now still contributes to soil texture and soil fertility on the terrace. Simulated and measures data for erosion and sedimentation differed considerably, which was due to the fact that the terrain of the impluvium is very stony, both on the surface and in the soil and in many places has crusts (Heirman, 2002).

Economic evaluation of Amrich jesr

The results of the financial and economic cost-benefit analysis for this individual jesr are rather low, with internal rates of return (IRR) below the social discount rate of 10.8 % as applied by Tunisian government since 1997 (Chapter 9). The low financial results are probably related to the low opportunity costs of family labour at the time of construction and the economic results would become higher when the downstream and other effects would be considered as well, as shown below.

11.6.2 Impact assessment and economic evaluation of WHT for whole watershed

In this example the implementation of water harvesting techniques in the Oued Oum Zessar watershed over the last ten years is evaluated economically, with inclusion of downstream and other effects, though the use of the FORCES-MOD model, as discussed in Chapter 9.

The Oued Oum Zessar watershed

As described in Ouessar (1999) and previous chapters, the Oued Oum Zessar watershed is located in the south-east of Tunisia near Médenine, covers an area of 33,600 ha and is inhabited by about 25,000 people.

Inputs by actors

In the period 1990-2000 the following areas has been covered with WHT: 657 ha with jessr, 5,725 ha with tabia's and 1,040 with contour stone ridges. The total investment costs amounted to 9.86 million TD. Maintenance costs were estimated at 5 % and the average lifespan of the works at 30 years. Annual exploitation costs depend on rainfall and various other factors and varied over the years from 0 – 210 DT ha^{-1}.

On-site and downstream effects

It is realised that WHT not only bring about on-site benefits of, in this case, mostly olive production in the hillsides, but also various downstream and indirect benefits (Fetoui, 1999; Sow, 1999; Yahyaoui and Ouessar, 2000). The research undertaken in Tunisia has taken into account: the reduced flood damages (on structures) downstream, the improved recharge of groundwater and the improvement of the quality of life and better income distribution in the watershed.

Economic evaluation of realisation of various WHT in Oued Oum Zessar watershed
The financial cost-benefit analysis took into account that average production values increased from 78 DT ha^{-1} before to 252 DT ha^{-1} after implementation. As in the case of a single WHT, the financial analysis for the total implementation showed a low internal rate of return (IRR). Since in the economic evaluation accounting prices were applied, whereby in the case of unskilled labour a conversion factor of 0.6 was used, positive results were obtained with an IRR of 13%. The subsequent extended cost-benefit analysis was executed in two steps The inclusion of reduced structure damaged by flooding, as result of the works, increased the IRR to 18 %. The subsequent inclusion of the recharge of groundwater, increasing irrigated land with 40 ha, and the improvement of the quality of life increased the IRR to 26 %. The social cost-benefit analysis, whereby higher weights were attached to benefits accruing to the relatively poor population in upstream and piedmont areas showed a further increase of IRR to 28 %. The details of these calculations are shown in Chapter 9. The respective type of benefits could all be calculated in monetary terms.

An alternative way of evaluating the impact of WHTs consists of the use of Multi-Criteria Analysis (MCA). This is not elaborated here, for details see De Graaff (1996). This is particular useful, when major categories of benefits can not be easily expressed in monetary or even quantitative terms.

11.7 Conclusions

Impact assessment of WHT, requires first of all a clear decision-making framework, considering agro-ecological and socio-economic circumstances and development policies. To assess all major impacts of WHT data have to be collected, through a careful monitoring of hydrological, erosion and other relevant physical and socio-economic effects at field and sub-watershed level. For effects at the level of the individual WHT the changes on water balances and nutrient balances could be assessed. Through the application of response functions the WHT level changes on water and nutrient balances can be translated in on-site effects on production. For the subsequent up-scaling from individual WHT to watershed level, GIS supported models and modules should be selected.

Thereafter a financial, economic, social and extended Cost-benefit analysis (CBA) is undertaken at individual WHT and farm level and thereafter at watershed level. In case not all major type of benefits could be expressed in monetary terms Multi-criteria analysis (MCA) could be applied as a decision-making and trade-of analysis tool. The results from the CBA would then form part of the set of criteria.

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CONCLUSIONS

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Thousands of years ago, the settlers of the arid and semi arid regions of the world and especially of the Mediterranean basin, have successfully understood how to cope with the spatial and temporal variability of the rainfall regime and mitigate the drought effects. They invented and practiced a large spectrum of water harvesting techniques (WHTs) ranging from small to large scale operations depending on the local conditions. For these WHTs different names were given by the local population, such as *jessr, cistern, negarin, mgoud, meskat, majel, fesquia, gavia, arenado, jable, natero, seguia,* etc.

The WHTs have been mainly assigned the role of supporting rainfed cropping and providing drinking water for domestic uses and animal watering. These continued to function in that manner until the beginning of the second half of the 20th century. At that time the new social and economic upheavals (alternative non agricultural income generation sources, migration, schooling, social transformation, etc.) and the technological developments started to raise the issue of viability and economic efficiency, and thus the desirability of any possible extension and expansion of these practices. However, WHTs may perform additional indirect functions such as flood prevention, ground water recharge, and erosion control which do normally not accrue to the (private) investor alone.

It is in this framework that the team of the WAHIA project managed to respond, although partially, to these questions raised. It has searched to develop an integrated approach to water harvesting to promote the sustainable development of water and soil resources in these zones based on limited data availability. The developed methodology was based on a holistic approach whereby the four main features of the watershed ecosystem have been taken into account namely: biophysical, economical, environmental, and social.

Impact assessment of WHTs requires first of all a clear decision-making framework considering agro-ecological and socio-economic circumstances and development policies. To assess all major impacts of WHTs data have to be collected through a careful monitoring of hydrological, erosion and other relevant physical and socio-economical effects at field and sub-watershed level. For effects at the level of individual WHTs the changes on water balances and nutrient balances could be assessed. Through the application of response functions these changes can be translated in on-site effects of production. For the subsequent upscaling from individual WHT to watershed level, GIS-supported models and modules should be selected. Thereafter a financial, economic, extended and social cost-benefit analysis is undertaken at individual WHT and farm level and subsequently at watershed level. Multi-criteria analysis is then applied as a decision-making and trade-off analysis tool. The criteria used should be based on the decision-making framework and should include the results from cost-benefit analyses.

A complete economic impact assessment of WHTs would require a considerable amount of data at several levels and over several years. In many situations these data are either not available or to costly to collect. The project has chosen for a less detailed methodology.

Furthermore, the project team was constrained by two major factors: a short project period of only 3 years and two consecutive drought years. Therefore the economic impact assessment was concentrated on the two principal WHTs in the two countries (jessour in Tunisia, seguias in Morocco) and use was made of relatively simple models and modules next to the data collected. In this way it succeeded in setting up a general methodological framework, in carrying out preliminary scenario trials and in developing a decision making tool which subsequently will need further validation with additional field data.

Through this detailed impact assessment and economic evaluation the importance was revealed of the integrated approach by an interdisciplinary team. The project made a detailed inventory of WHTs in the two reference areas, and designed and applied interesting water balance measurement methodologies and hydrological models for subsequent use in an economic impact assessment. The profitability of the WHTs depends largely on the chosen criteria and the scale of investigation. WHTs in dry zones are only marginally efficient in economic terms if considered from the perspective of the individual beneficiary (financial cost-benefit analysis). However, when off-site effects are accounted for, the efficiency improves substantially. For example, the cost benefit analysis of the Amrich jessr showed that the on-site effects alone can not justify the investment; however, when the analysis was extended to the whole watershed (off site effects) the results were much more positive. This is why some government incentives and subsidies could be justified such as the maintenance of the different traditional WHTs on the islands of Lanzarote and Fuerteventura of the Canaries (Spain) in order to preserve the landscape as tourist attraction. Another example consists of the groundwater recharge structures in hilly areas in Tunisia, which benefit the downsteam population.

Nevertheless, further refinements are needed to better include all possible impacts (positive and negative) that could follow the installation of WHTs. The interactions between upstream and downstream areas have to be addressed thoroughly to ensure optimal partitioning of natural resources between different end users in order to come out with fully integrated development plans which take into consideration all the necessary technical, agricultural, socio-economic and institutional aspects and inputs. Thereto, the intensive use of geographical information systems (GIS) and information technology (IT) and modelling can play an important role in transforming the obtained results in the form of Decision Support Systems (DSS) for policy-makers in the area of natural resource management. These could also be used to assess under which agro-ecological and socio-economic conditions investment in water harvesting practices could be a viable undertaking in dry Mediterranean areas or in other regions with similar agro-ecological conditions (e.g. Southern Europe, Sahel).

The project has strengthened the north-south and south-south scientific collaboration through a dense exchange program of scientists and capacity building of technicians and students from the four partner institutions. It has succeeded also in involving the stakeholders, the farmers and the local development agencies, dealing with the day-to-day rural development problems of the local populations, as full partners who are in fact the target users and the final field appliers of the developed methodologies and tools.

This scientific collaborative network is expected to last beyond the time frame of the WAHIA project and even to expand to integrate other partners as it was the case with Laguna University during the final seminar. The allocated budget shall be viewed as 'seed money' for future intense and upgraded scientific cooperation programs between the partner institutions.

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Abstract

This book constitutes the proceedings of the final seminar of the European Union-funded research project "WAHIA" (Water Harvesting Impact Assessment) held in March 2002 on Lanzarote (Canary Islands). It covers the research results of this project, which was executed in southern Tunisia and southern Morocco by a consortium of Wageningen University (The Netherlands), "Institut des Régions Arides" (Tunisia), University Ibnou Zohr (Morocco) and Ghent University (Belgium), and it also presents similar research undertaken by the University of La Laguna (Canary Islands). In the framework of the project an impact assessment and economic evaluation was undertaken of water harvesting techniques for the watersheds of Oued Oum Zessar (Tunisia) and Oued Talkjounte (Morocco). Based on (geo-)hydrological research in which surface flow, erosion, sedimentation and groundwater recharge were quantitatively assessed, models were developed that simulate these processes at the scale of individual water harvesting techniques and at catchment-scale. The measured data and models generated input data for the impact assessment in which physical effects were translated in economic terms. A tool for decision-making was developed to assist decision-makers in other areas to analyse which water harvesting techniques may suit in a certain location and which on-site and downstream effects may have to be taken into account.

Résumé

Ce livre est le compterendu du séminaire final du projet de recherche, financé par l'Union Européenne, "WAHIA" (Analyse des Impacts de Collection d'Eau), qui a eu lieu en mars 2002 à Lanzarote (Iles Canaries). Il présente les résultats dudit projet, qui a été exécuté dans le sud de la Tunisie et le sud du Maroc par un consortium de l'Université de Wageningen (Pays-Bas), l'Institut des Régions Arides (Tunisie), l'Université Ibnou Zohr (Maroc) et l'Université de Gand (Belgique), et aussi les résultats de recherche dans ce domaine de l'Université de La Laguna (Iles Canaries). Dans le cadre du projet une analyse des impacts et une évaluation économique des techniques de collection d'eau pour les bassins versants de l'Oued Oum Zessar (Tunisie) et de l'Oued Talkjounte (Maroc) ont été faites. Basé sur la recherche (géo-)hydrologique dans laquelle le ruissellement, l'érosion, la sédimentation et la recharge de la nappe phréatique ont été quantifiés, des modèles ont été développés afin de simuler ces processus au niveau des techniques individuelles de collection d'eau et au niveau des bassins versants. Les données mesurées et les modèles ont engendré des données d'entrées pour l'analyse des impacts dans laquelle les effets physiques ont été traduits en termes économiques. Un système de prise de décisions a été développé afin d'assister les dirigeants d'autres régions à analyser quelles techniques de collection d'eau pourraient être efficaces dans une certaine situation, et quels effets sur le site et en amont devraient être pris en considération.

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